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FINAL REPORT ON

BUOYANCY AND STABILITY CHARACTERISTICS OF THE HUMAN BODY AND PERSONNEL FLOTATION DEVICES

submitted to the

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
WASHINGTON, D. C.

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Arthur D Little, Inc

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ABSTRACT

This study was directed toward providing a technical basis on which to judge statistically the effectiveness of buoyancy and stability provided by personnel flotation devices for the general boating population. A detailed theory of PFD buoyancy and stability has been formulated. Statistical methods for evaluating the adequacy of the buoyancy and stability provided by a PFD in terms of fraction of the population adequately served have been developed.

Tasks performed include a literature search, a theoretical analysis of the problem, a measurements program on a limited population to determine relevant physical characteristics, a statistical data analysis program to illustrate the adequacy of added buoyancy and stability in terms of fraction of the population served, and the design of a larger-scale test and analysis program to obtain statistically reliable data on the general boating population.

SUMMARY

This study was directed towards an experimental and analytical program to determine the buoyancy and righting characteristics of the human body alone and when coupled with a personnel flotation device. The objective was to provide the data upon which to base criteria for judging the effectiveness of personnel flotation devices with respect to both the buoyancy and stability provided in terms of the fraction of the boating population adequately served.

The contract for this study called for but was not limited to the performance of the five following tasks:

- Conduct a literature search and analysis of existing pertinent information.
- Perform a theoretical analysis of the problem.
- Design and perform an anthropometric test program on a special population to obtain necessary statistical information on the relevant physical characteristics of the boating population.
- Analyze the data for the special population and present results in terms of statistical measures of buoyancy and stability requirements.
- Design a test and analysis program for establishing the buoyancy and stability characteristics of the general boating population.

This work was carried out in close cooperation with the U. S. Coast Guard Office of Research and Development. With the concurrence of the contract monitor, during the course of the work, relative emphasis among the tasks was redirected as required to accomplish the objectives. The results of our work are:

- The initial literature search showed that there had been no general analytical treatment of the buoyancy and stability problem which defined the relevant characteristics of either the boating population or of personnel flotation devices.

  Later in the program after these characteristics were defined, our continuing literature search disclosed little statistical information in useable form. As a result of these two deficiencies, increased emphasis was directed toward our analytical and experimental efforts.

- Our analytical effort resulted in a general statistical theory of buoyancy and stability which delineates the relevant physical characteristics of both the boating population and personnel flotation devices.

- Equipment for the experimental program was designed, tested and refined, using members of the experimental team.

- A detailed statistical evaluation of the literature showed that there were major statistical differences between the physical characteristics of service personnel and the general population. As a result, testing of a special population of service personnel would not provide statistically useful data.

Emphasis on our experimental testing program was therefore redirected toward testing a limited sample of adult men and women especially selected to span the characteristics of the general population.

- Data analysis was directed toward the qualification of our limited sample and statistical methods of evaluating the adequacy of added buoyancy and stability. Our results show that:

  1. For those physical characteristics where statistical data for the general population are available, analysis shows no statistically significant differences between the especially selected sample and the general population. As a result, one would not expect major contradictions between the findings for the especially selected sample and the general population. However, because of the limited nature of the sample, it is subject to statistical uncertainty. For this reason no attempt should be made to generalize the results in this work to the general boating population until further statistical verification is completed.

  2. Buoyancy requirements for an individual are determined by his submerged weight, state of inflation of the lungs, water density, and body volume to be floated above water. Our results for adults is shown in Figures 5 and 6 in the text. The results are general in that the buoyancy requirement can be determined for an arbitrary fraction of the population from these curves.

Typically, in fresh water at normal lung volume (i.e., functional residual volume), it requires 12 pounds of buoyancy to float 60% of the adult male population with a volume equivalent to that of the head above water. In adult females, the similar requirement is 8.5 pounds.

3. Our experiments and analysis show that the required turning moments or stability requirements for an individual are determined by the density of water, the subject's orientation, state of inflation of the lungs, distance from his center of buoyancy to center of gravity, submerged weight and two linear body dimensions. There are two turning moments applied by a personnel flotation device. They are both a function of a subject's orientation. The first moment is in addition a function of the added buoyancy and the linear dimensions of the subject. The second moment is a function only of the added buoyancy and the location of the center of buoyancy of the personnel flotation device with respect to the subject.

   The buoyancy to be provided by a personnel flotation device is determined as in result 2. above. With a defined lung volume, the only undetermined quantities relate to the location of the center of buoyancy of the personnel flotation device. In Figure 11, the fraction of the population that will be rotated through vertical from the face-down to face-up position is shown as a function of the distance from the body center line to the personnel flotation device center of buoyancy.

Here again, the result is a general one in that the distance required for any desired fraction of the population can be obtained from this curve. Typically, to rotate 60% of the population through vertical, this distance must be 7 inches for adult females and 6 inches for adult males.

The center of buoyancy of the personnel flotation device must not be too far down the chest for either of two reasons; first, in the face-down position, the subject must be initially rotated toward vertical, and second, in the face-up position, the subject must not come to equilibrium too far back. The vertical distance requirement for varying fractions of the population for a given buoyancy is shown for these two conditions in Figures 12 and 13. Typically, the center of buoyancy of the PFD must not be more than 5 inches below the top of the breast bone (suprasternal notch) if 97% of the adult male and adult female population are to be correctly rotated initially from the face-down position and are to have an acceptable face-up equilibrium orientation.

- In our limited sample, there are significant differences between adult males and females in terms of the added buoyancy requirement and the location of the center of buoyancy to provide required turning moments. It is anticipated that when the general boating population including children is considered, that the range of these differences will be extended.

- The work described in this report considers fixed lung volumes with PFD buoyancy and center buoyancy fixed with respect to the subject at all orientations. The theoretical treatment is sufficiently general to treat the case in which the PFD buoyancy and location of center of buoyancy varies with orientation; however, this has not been done as yet.

- The investigation of buoyancy was referenced to fixed bony anatomical reference points. Specifically, the head volume above the jaw-line and the head plus neck volume above the top of the breast-bone. We anticipate that an acceptable buoyancy criteria will be specified on the basis of some fraction of the incremental volume between these two anatomical points of reference. At the time of writing, insufficient statistical data are available on which to base a recommended criteria.

INTRODUCTION

STATEMENT OF PROBLEM

Up to the present time, design, testing and evaluation of personnel flotation devices (PFD) have been in the main empirical.[1,2,3] The human body characteristics which influence stability and buoyancy requirements of PFD's have not been studied in a definitive manner. A PFD has four main requirements:

1. Provide stability characteristics to rotate an individual into a favorable floating position for maintenance of respiratory function.

2. Provide sufficient buoyancy to maintain respiratory function for individuals that have been rotated into a favorable position.

3. Provide characteristics which will assure maximum usability.

4. Provide buoyancy and stability characteristics which can serve the largest reasonable fraction of the boating population consistent with usability considerations.

Empirical tests on live subjects or dummies indicate that, although providing sufficient buoyancy poses no serious difficulties, the problems associated with stability are not easily solved. In addition, a PFD which meets buoyancy and stability requirements may pose serious problems of wearability and usability.

Sufficient data exists[4,5,6] to indicate that the results of the present study on male and female adults may not apply to all segments of the boating population. The limited available data in this respect indicate that those body characteristics which are likely to influence buoyancy and particularly stability vary with age. The data which are particularly pertinent are those concerned with anthropometric measurements and fat distribution calculated as a proportion of either total body weight, total body volume or total body length. From the point of view of stability characteristics, the volume distribution is of particular importance. These data also indicate that it is likely that the proportioning of these characteristics becomes stable at the age of approximately 15 years for both sexes. However, at this time, because of the limited available data, no firm predictions can be made until actual measurements are obtained on the boating population. Therefore, although the present study defines the problem for the adult male and female population based on a limited sample of this population, the segments into which the general boating population must be divided in order that it may be served adequately by PFD's must await statistically valid measurements on this population.

SCOPE OF STUDY

The focus of this program has been to provide a scientific basis or methodology for establishing criteria on which to judge the adequacy of the buoyancy and stability provided by personnel flotation devices of varying and presently unspecified design. The aims of the present program have been:

- to develop effectiveness criteria for personnel flotation devices;
- to develop a general theory of buoyancy and stability provided by personnel flotation devices;
- to validate the theory through experimentation on specific individuals of known physical characteristics;
- to devise statistical methods of relating device performance as represented by design parameters to the requirements of the general population.

In this way, it is believed that the performance of a personnel flotation device of arbitrary design can be evaluated or rated in terms of its ability to satisfy the buoyancy and stability requirements of an arbitrarily large predetermined fraction of the general boating population.

Studies of existing PFD's in terms of buoyancy, stability and wearability characteristics were beyond the scope of this study. Instead, the study was confined to examining existing pertinent information and, where this was not available, obtaining the necessary information on a limited sample of human subjects. The information was used to perform a theoretical analysis of buoyancy and stability requirements as this pertains to the statistical characteristics of the boating population.

LIMITATIONS

It should be strongly emphasized that the present effort has been largely devoted to the development of a methodology for establishing the requisite criteria. The methods developed and results reported in this document are intended to illustrate how one can proceed toward accomplishing the desired objectives rather than the accomplishment itself. For this reason it is necessary to state the following limitations on the work reported here.

- The statistical distribution curves for percentage of the population in each case are obtained from a limited experimental sample. No attempt should be made to extrapolate the present results to the general boating population without further statistical validation.

- The present work is limited to the consideration of still fresh water. Salt water will ease buoyancy requirements; however, it also will adversely affect stability. Extrapolation of present results to salt water requirements and performance are unjustified without further theoretical and experimental verification.

APPROACH

BUOYANCY

The approach to the buoyancy problem was based on the fact that the amount of buoyancy required for an individual is a function of the fraction of the body volume required to be out of the water and the submerged weight of the individual subject for a particular lung volume. Therefore, it was necessary to obtain statistical information on the volume of head and neck, and submerged weight of the individual subjects at various reference lung volumes.

If we take the worst condition, i.e., an individual entering the water in the unconscious state, his lung volume would probably be near functional residual capacity plus variations due to tidal volume. However, in order to make reproducible measurements it was believed that lung volumes other than residual volume (volume of air left in the lungs after full expiration) would be difficult to obtain in a reproducible manner. Therefore, measurements were to be made with subjects at residual lung volume.

STABILITY

Our approach to the stability problem was based on the fact that the moments required to maintain the fully submerged subject (at residual lung volume) at arbitrary trunk inclination angles could be measured directly. In addition, the effects of linear body dimensions, submerged weight and added buoyancy could be evaluated.

The simulation of the unconscious state by requesting subjects to float in the "relaxed state" may be unrealistic because the completely relaxed state is difficult to achieve. On the other hand, we believe that the subject's idea of the relaxed state gives a statistical variation of the possible configurations which might represent the problem as it actually exists. In addition, the position of the head was theoretically evaluated as being a factor of prime importance in the stability problem, especially when it is floated out of the water by the added buoyancy of a PFD. Repeated tests on the same subject in the relaxed state showed that for a given subject the stability curves were reproducible within narrow limits.

Fresh still water was chosen as the condition under which all experimental and theoretical efforts would be conducted.

LITERATURE SEARCH

With the above approaches in mind, a detailed review of the literature provided little information of value of the volume of the head and neck. The extent of the literature on this subject is based on the works of Braune and Fischer[7] who dissected three cadavers in 1889, Fischer[8] who dissected one cadaver in 1906 and Dempster[9] who dissected eight cadavers and reported the results in 1954. Therefore, the total sample for the determination of body segment, masses and volumes consists of 12 cadavers. These cadavers had a mean weight of 60 kg while the mean weight of 4060 U.S. Air Force personnel reported by Hertzberg <u>et al.</u>[10] was 73.3 kg. Because of the limited sample

size and its strong bias towards small subjects it was decided not to base analyses of the buoyancy and stability problem on this early work. Literature was searched for information on the submerged weight of human subjects. This quantity is a function of tissue density, body volume and lung volume and has been obtained in the past for determinations of body composition. We therefore found a significant amount of data on tissue density but little data on body volume. In addition, the data was almost exclusively on male subjects. The literature was searched for information on stability characteristics of the human body and no data of this nature were discovered.

Since our needs were specific and dependent in large measure upon obtaining measurements on the same subjects, it was decided that the quantities required had to be obtained by direct measurements on human subjects. A large-scale statistical testing of the general population to determine the critical parameters to the required statistical accuracy was beyond the scope of the program. Therefore, it was decided that measures would be made on a selected limited sample of subjects.

THEORETICAL ANALYSES

GENERAL ACCEPTABILITY CRITERIA

In the development of the program, it has been necessary to establish a number of hypotheses relating to the acceptability of the performance of personnel flotation devices. These include the following:

- The device must provide adequate buoyancy to float the subject with "sufficient freeboard" to assure that his nose and mouth are well above water under the condition that he is in the "proper orientation."
- If the subject is in an "improper orientation" the device must provide "sufficient" turning moments to rotate the subject and to maintain him in the "proper orientation."
- The device must provide "sufficient freeboard" and "sufficient turning moments" under the "worst case" of subject lung volume and flotation equilibrium.
- It must be possible for a given device to "evaluate" quantitatively the fraction of the population that will be adequately served with respect to both buoyancy and stability.

it is the words "sufficient freeboard," "proper or improper orientation," "sufficient turning moments," "worst case," end "fraction of the population adequately served," that have provided the theoretical and experimental thrust for this program. Rather than rendering arbitrary judgments, we have chosen to illustrate how physical measurements can be made on a representative sample of the boating population to generate curves relating performance to fraction of the population. Using these curves, it is possible to do either one of two things:

- Specify the physical design parameters of a personnel flotation device to provide a predetermined level of performance to a predetermined arbitrarily large fraction of the population;

or to:

- Rate a personnel flotation device with arbitrary design parameters in terms of the fraction of the boating population that will be adequately served with respect to buoyancy and stability provided by this particular design.

Either one of these alternatives could serve as the basis for establishing evaluation criteria. However, there is a basic philosophical difference in the two approaches. In the first case, the criteria specify the design parameters that if edhered to will serve a predetermined and stated fraction of the population. By inference then, the criteria accept the fact that a predetermined remaining fraction of the population need not be served and there is no motivation for a device designer to

make his device larger or more cumbersome to serve this remaining fraction. On the other hand, if the second approach is used, devices of varying designs are "scored" individually on the basis of the fraction of the population served with respect to buoyancy requirements and stability requirements. The individual designer may improve his score by enlarging his device or making it more cumbersome.

In the final analysis, it may be desirable to use both approaches simultaneously in that a minimum criteria could be established for basic approval by the Coast Guard with a scoring criteria for evaluating higher performance personnel flotation devices.

THEORY OF BUOYANCY

Submerged Weight

When a subject exhales fully his lungs are deflated to residual lung volume. At this point, the subject has negative buoyancy in fresh water. We have defined this amount of buoyancy as the subject's submerged weight, S. The submerged weight must be exactly equal to the difference between the subject's total weight in air and the weight of water displaced by the fully submerged subject. That is

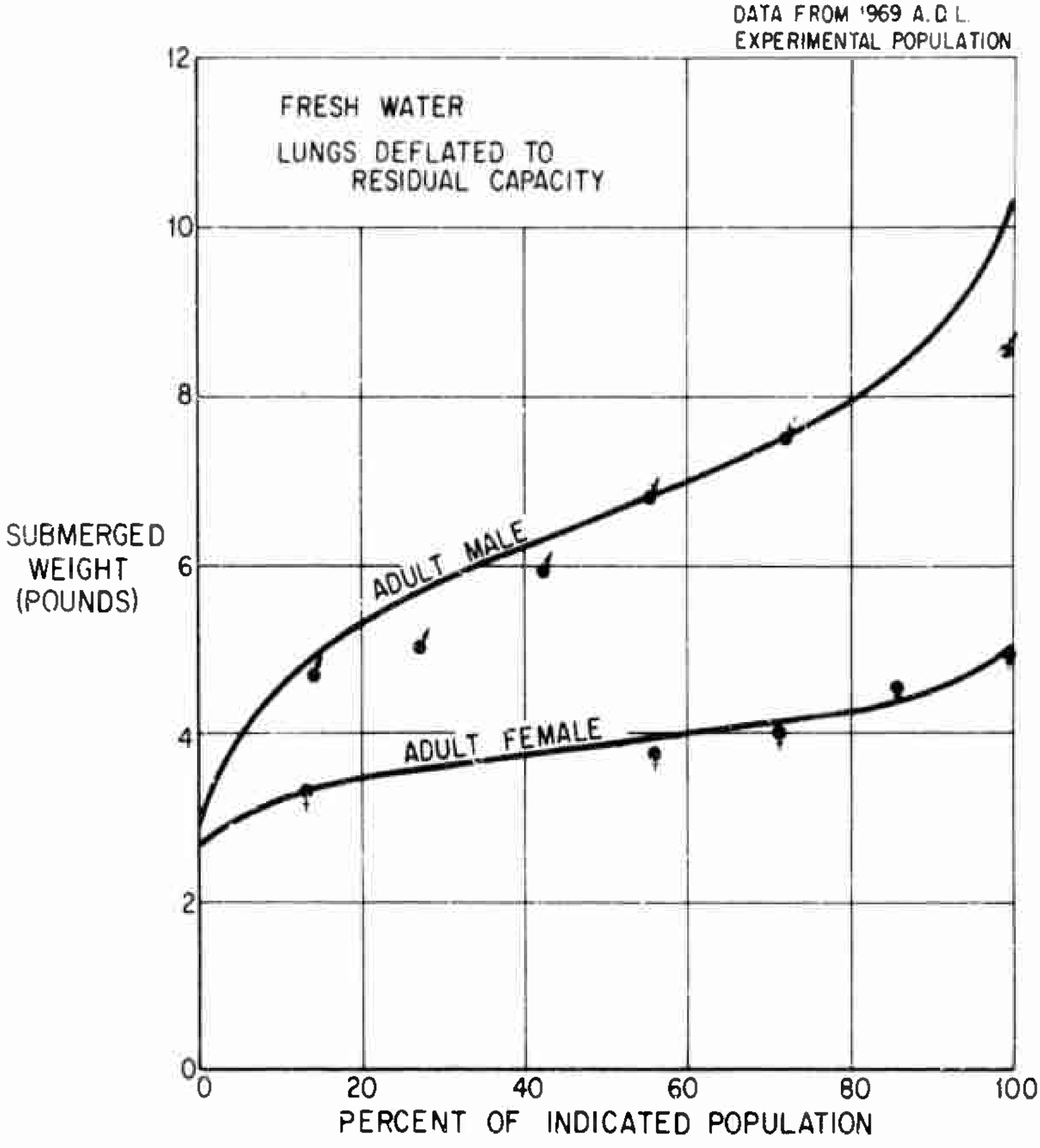
$$S = W - \rho_w V_T \qquad (1)$$

where

S	is the subject's submerged weight at residual lung volume.
W	is the subject's weight.
ρ_w	is the density of water.
V_T	is the subject's total body volume including residual lung volume.

A series of experiments were performed on the limited sample of adult males and adult females to measure the value of submerged weight for each individual. This population was limited to eight adult male subjects and seven adult female subjects. The subjects were especially selected to span the range of body shapes and sizes that we anticipated might be found in the general adult population. Because of the limited sample size and biased sampling method no attempt should be made to generalize the results obtained. However, it should be emphasized that, if data were obtained from a randomly selected population sample of significant size, then it would be possible to construct a probability distribution function for submerged weight over the population and to specify statistical reliability of this distribution function.

To illustrate the type of result that would be obtained, the limited population sample was used to generate probability distribution functions for submerged weight under the assumption that the distributions can be represented by a normal distribution. The results are shown in Figure 1. In this figure, the points represent the histograms obtained from data on the limited population. The solid lines represent normal distributions fitting the same data. A discussion of the relationship between precision of measurements of physical characteristics of a single individual and the related physical statistical characteristics of the general population is given on page 55.



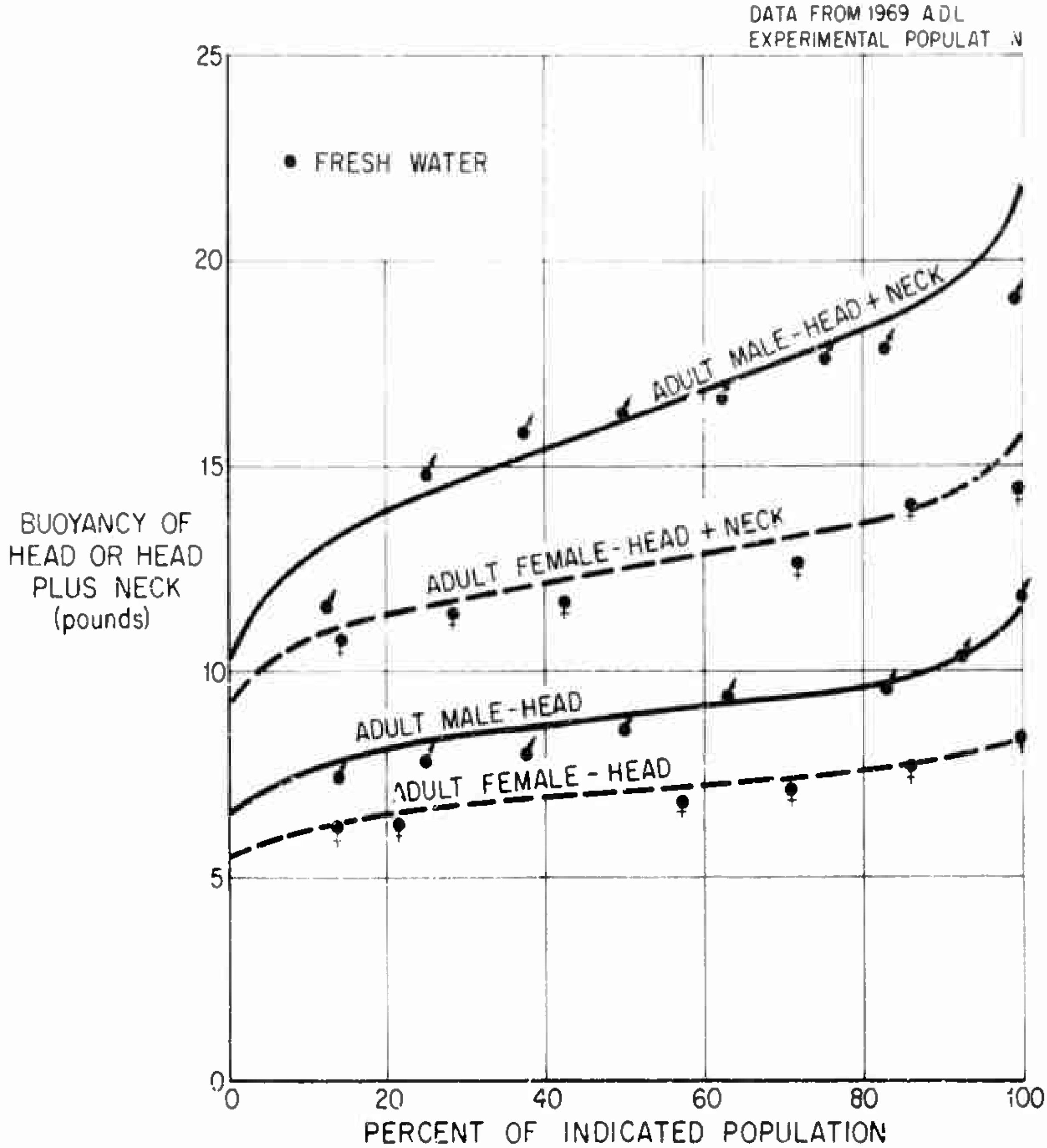
PERCENT OF POPULATION HAVING SUBMERGED WEIGHT EQUAL TO OR LESS THAN INDICATED VALUE.

FIGURE 1

Head and Head Plus Neck Volumes

If one were to provide additional buoyancy equal only to the submerged weight of a subject, the subject would then be floated with zero freeboard. It is therefore necessary for a personnel flotation device to provide an amount of buoyancy in excess of the maximum probable submerged weight. This must assure that essentially all of the population will be floated with their nose and mouth "well above" water if they are in a "proper orientation." To evaluate how much additional buoyancy might be required, a series of experiments were conducted on the limited population sample to measure the volume of the individual subject's head and the volume of their head plus neck. Here again, because of the limited and non-random sample, no attempt should be made to extrapolate the present results to the general population. The results are to be used for illustrative purposes only.

Through a measurement of the volume of the head or head plus neck, one can determine the loss of body buoyancy associated with bringing this volume above water. This loss of buoyancy must be compensated for through an addition to the buoyancy provided by the personnel flotation device The results of the experiment are shown in Figure 2. Here again, the points represent the experimental data and the curves represent a normal distribution fitting these data.



PERCENTAGE OF INDICATED POPULATION HAVING HEAD OR HEAD PLUS NECK BUOYANCY EQUAL TO OR LESS THAN INDICATED VALUE.

FIGURE 2

Theoretical Development

If a subject is in flotation equilibrium, the sum of the vertical forces acting must be equal to zero, that is

$$\sum F_y = 0 \tag{2}$$

where F_y indicates the individual vertical forces. In our case there are three vertical forces acting. These are:

W	-	The subject's total weight acting vertically downward.
$\rho_w(V_T - V_o)$	-	The buoyancy of the submerged portion of the subject's body acting vertically upward.
B	-	The additional buoyancy provided by the personnel flotation devices.

The auxiliary quantities are defined as

ρ_w	-	The density of water.
V_T	-	The subject's total body volume including lung volume.
V_o	-	The volume of the subject's volume floated above water.

Summing these vertical forces, we obtain

$$\sum F_y = W - \rho_w(V_T - V_o) - B = 0 \tag{3}$$

Therefore,

$$B = W - \rho_w V_T + \rho_w V_o \tag{4}$$

However, we have previously defined the quantity $W - \rho_w V_T = S$, that is, the submerged weight when the lungs are deflated to residual volume.

The additional buoyancy that a personnel flotation device must provide to float a volume V_o above water for a subject whose lungs are deflated to residual volume and whose submerged weight is S, is given by

$$B = S + \rho_w V_o \tag{5}$$

If we wish to float this subject with e volume equivalent to that of his head above water, at this particular lung volume, then $V_o = V_h$ where

V_h is the volume of the subject's head.

If we wish to float this subject with a volume equivalent to his head plus neck above water at this particular lung volume, then $V_o = V_{h+n}$ where

V_{h+n} is the volume of the subject' head plus neck.

We can therefore write for each subject, at residual lung volume, expressions for the buoyancy required to float either his head or head plus neck above water. These expressions are of the form:

$$B_n = S + \rho_w V_h \tag{6a}$$

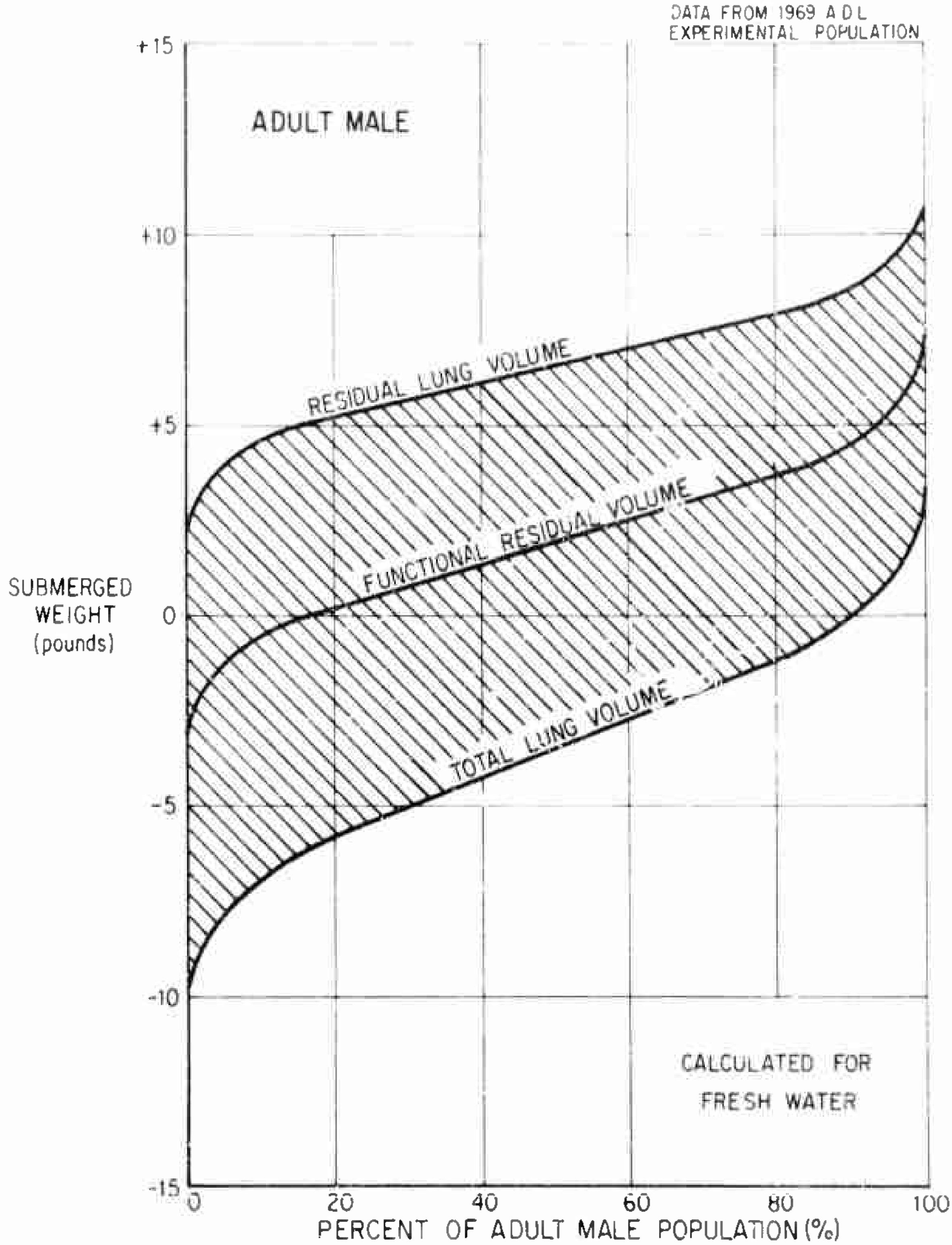
$$B_{h+n} = S + \rho_w V_{h+n} \tag{6b}$$

Effect of Changing Lung Volume

A subject can not for long maintain his lungs at residual lung volume. In normal respiration, the lungs are deflated to a volume corresponding to functional residual volume rather than to residual volume. The difference in these two volumes is the expiratory reserve volume for each of our subjects. This quantity was measured and its effect on submerged weight can be calculated.

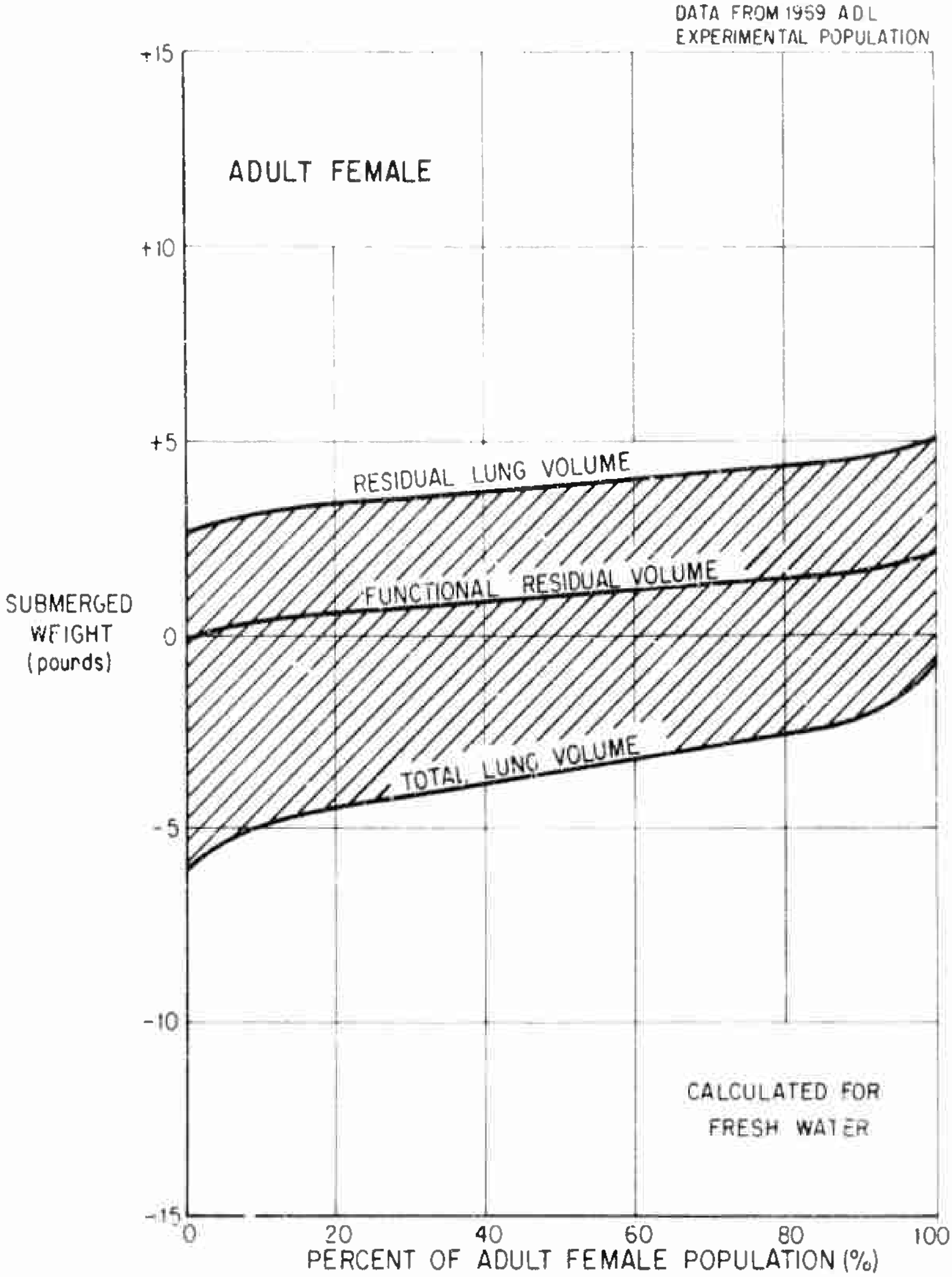
An individual can inflate his lungs to a maximum volume above residual volume by an amount defined as his vital lung capacity. We have measured this quantity for each of our subjects and calculated its effect on submerged weight.

The effect of changing lung volume on submerged weight for the adult male and female population is shown in Figures 3 and 4, respectively. In these figures it is seen that a man can reduce his submerged weight by approximately 5 pounds by inflating his lungs to functional residual capacity and by 10 pounds by inflating his lungs to total lung volume. An adult female can reduce her submerged weight by approximately 3 pounds by inflating her lungs to functional residual capacity, and by approximately 8 pounds by inflating her lungs to total lung volume.



PERCENT OF ADULT MALE POPULATION HAVING A SUBMERGED WEIGHT EQUAL TO OR LESS THAN THE INDICATED VALUE FOR DIFFERENT LUNG VOLUMES.

Figure 3



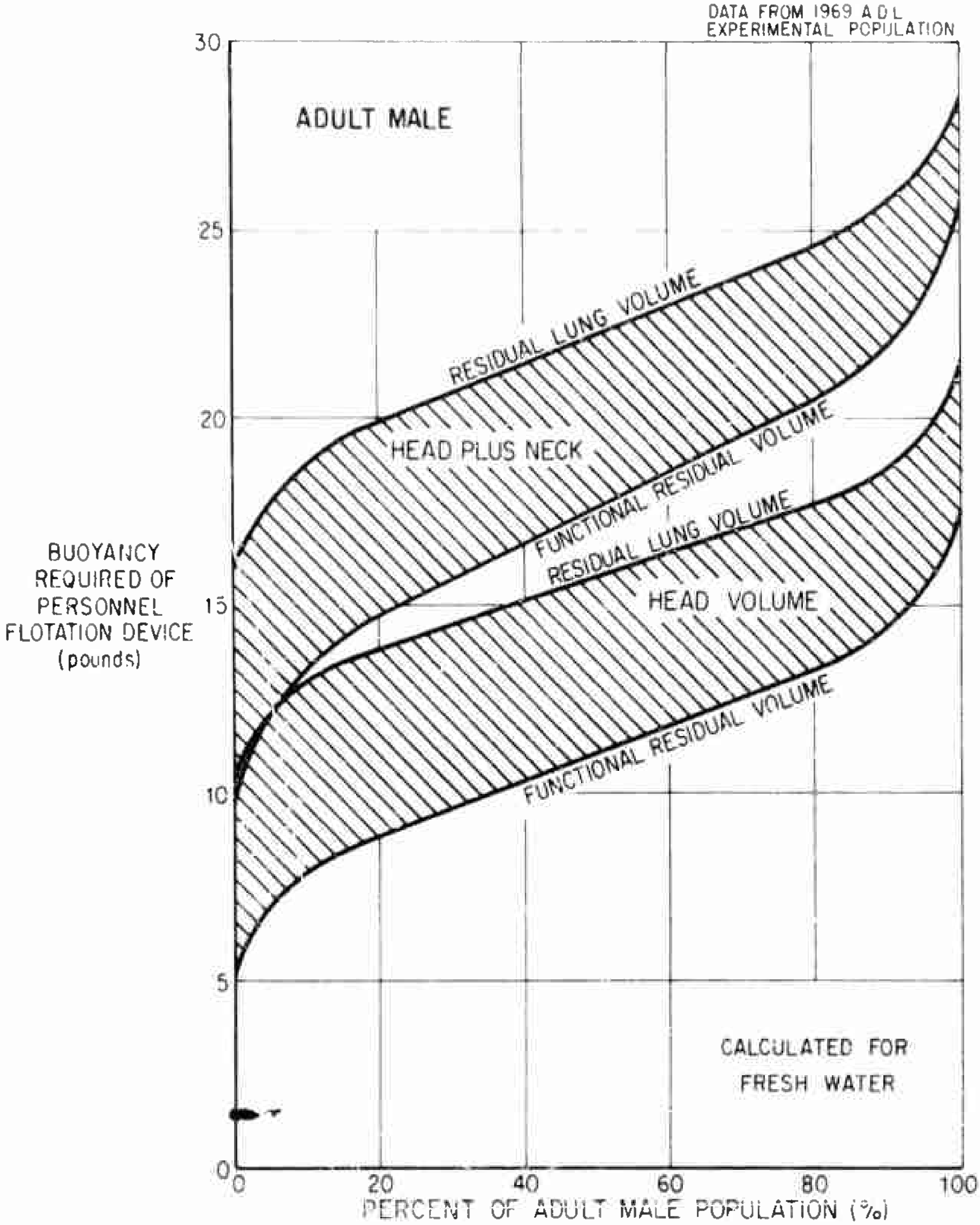
PERCENT OF ADULT FEMALE POPULATION HAVING A SUBMERGED WEIGHT EQUAL TO OR LESS THAN THE INDICATED VALUE FOR DIFFERENT LUNG VOLUMES.

Figure 4

Statistical Buoyancy Requirement

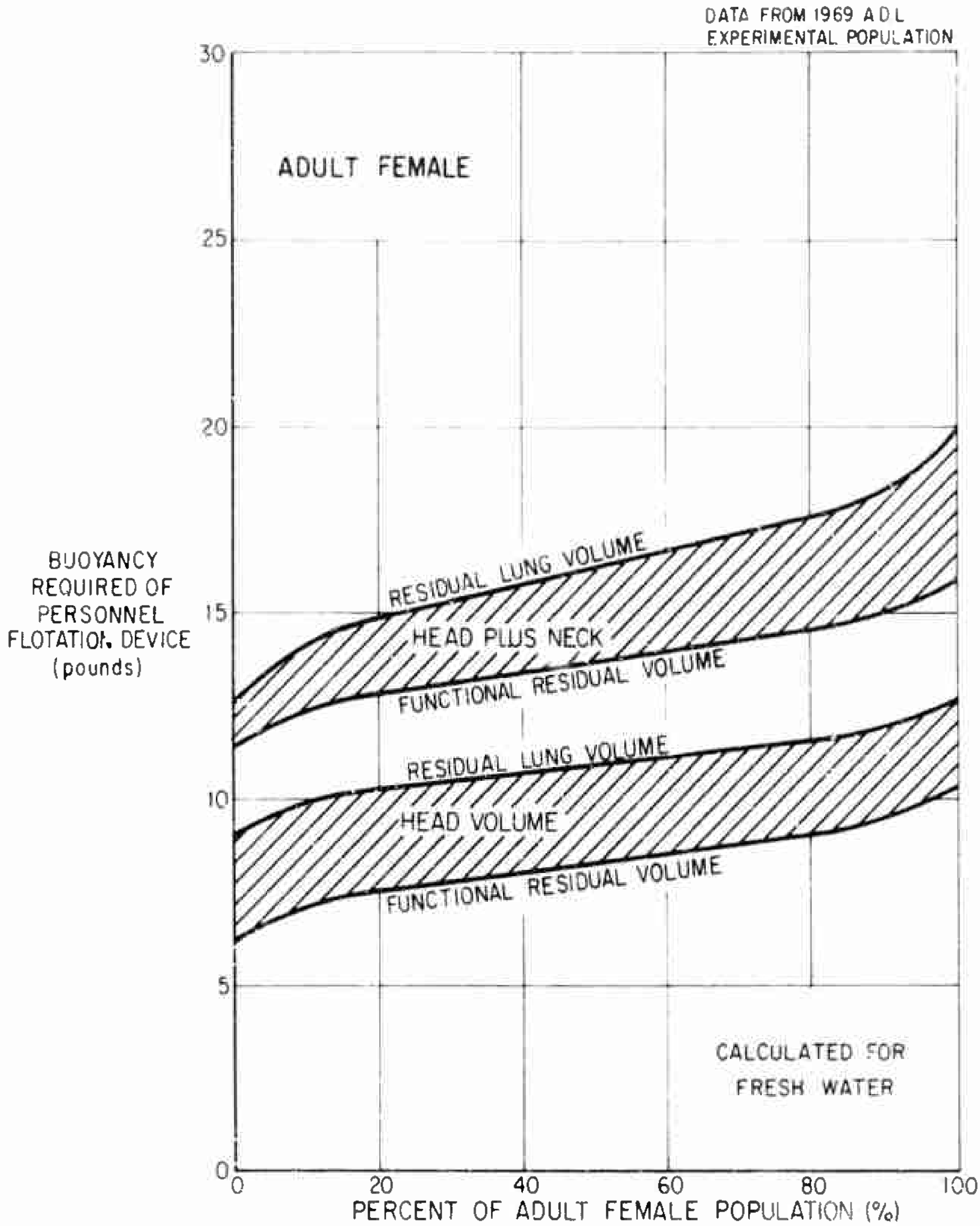
Referring to equations (6a) and (6b) we have expressions for the buoyancy required to float a volume equivalent to that of the head or head plus neck above water for an individual subject when the lungs are deflated to residual volume. Each subject's head and head plus neck volume has been measured as well as his submerged weight at residual volume. It is therefore possible, using these equations, to calculate the additional buoyancy that must be provided by the personnel flotation device for the residual lung volume case. We have also measured the effect of changing lung volume on submerged weight for each subject. It is therefore possible to calculate the individual's additional buoyancy requirement at other than residual lung volume.

We have calculated the additional buoyancy required of a personnel flotation device for each subject at residual lung volume and at functional residual volume. It is our belief that the probability of a subject maintaining his lung volume at significantly greater volume than functional residual volume for long times is small. Therefore, the functional residual volume case is the only case considered in addition to the worst case of residual volume. The data obtained from the limited ADL population have been treated statistically to yield the probability distribution functions for additional buoyancy required of a personnel flotation device. The results obtained for additional buoyancy required for the adult male and female populations are shown in Figures 5 and 6, respectively.



BUOYANCY REQUIRED TO FLOAT INDICATED FRACTION OF ADULT MALE POPULATION WITH A VOLUME EQUAL TO OR GREATER THAN THE HEAD OR HEAD PLUS NECK ABOVE WATER.

Figure 5



BUOYANCY REQUIRED TO FLOAT INDICATED FRACTION OF ADULT FEMALE POPULATION WITH A VOLUME EQUAL TO OR GREATER THAN THE HEAD OR HEAD PLUS NECK ABOVE WATER.

Figure 6

THEORY OF STABILITY

In the treatment of stability, we will be dealing with subjects that are in flotation equilibrium. However, they will not necessarily be in rotational equilibrium. This condition represents a "worst case," since larger turning moments must be provided by a personnel flotation device to rotate a subject at flotation equilibrium with freeboard than under the fully submerged condition.

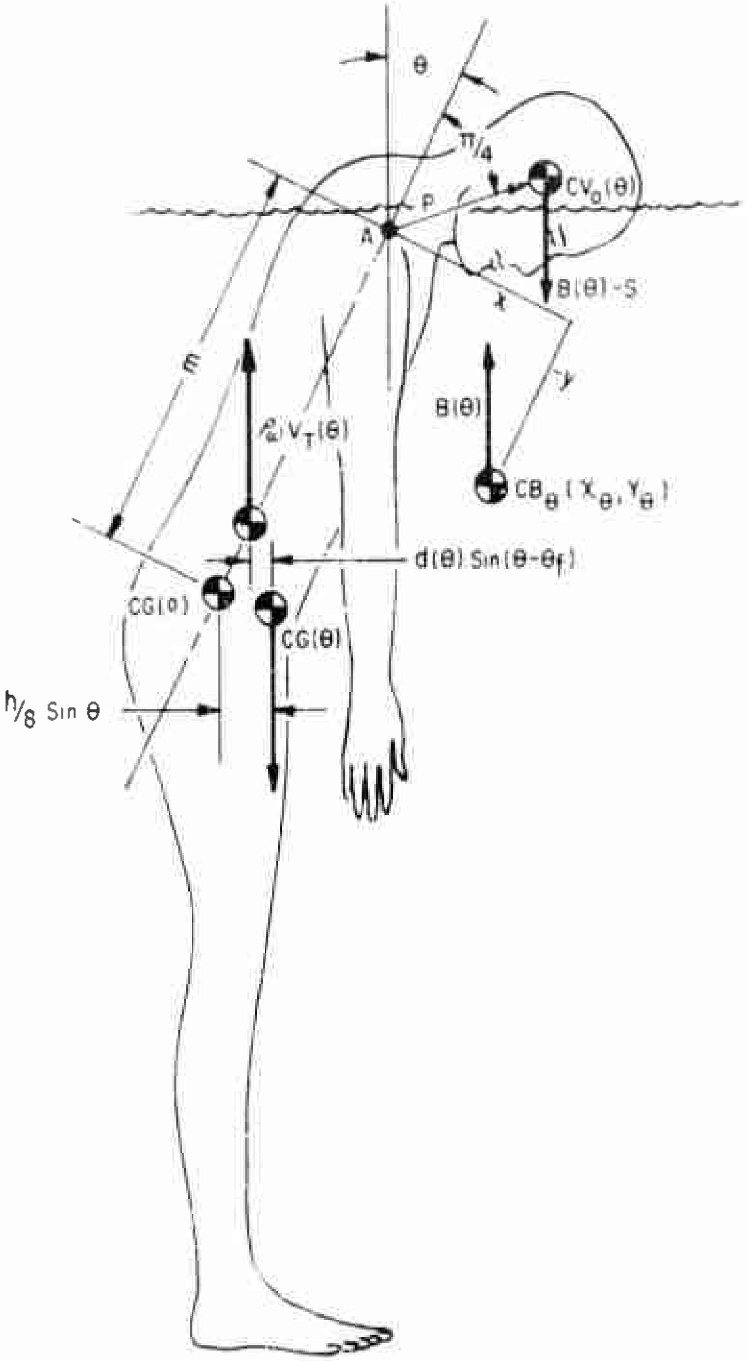
The present theoretical treatment will be restricted to rotation about a transverse axis. This implies fore and aft rotation only.

It is observed that all of the forces acting on the subject are acting vertically, and further, that the sum of the forces at flotation equilibrium is zero. Under these conditions, it follows that the vertical forces can be fully resolved into a series of equal and opposite forces acting at different horizontal locations. Therefore, the vertical forces represent a series of couples acting on the subject. This leads directly to the conclusion that the moments acting on the subject are independent of the choice of the point about which the moments are taken.

Head Flexed

If we consider a subject in flotation equilibrium though not necessarily in rotational equilibrium in the prone position, with head flexed and equipped with a personnel flotation device, we have the situation diagrammed in Figure 7. In Figure 7 we define

θ	is the trunk inclination angle to the vertical.
CC(0)	is the location of the subject's center of gravity when the trunk is erect.
$CC(\theta)$	is the location of the subject's center of gravity when the trunk is inclined at the angle θ to the vertical.
$CV_T(\theta)$	is the center of total buoyancy when the trunk is inclined at the angle θ to the vertical.
$CV_o(\theta)$	is the center of buoyancy of the subject's body volume floated above water.
$CB(\theta)$	is the center of buoyancy of the personnel flotation device.
W	is the subject's weight in air.
$\rho_w V_T$	is the subject's total buoyancy
S	is the subject's submerged weight at a particular lung volume, $S = W - \rho_w V_T$
$B(\theta)$	is the buoyancy provided by the personnel flotation device at flotation equilibrium when the trunk is inclined at the angle θ
$x(\theta), y(0)$	are the coordinates of $CB(\theta)$ relative to a system fixed on the body axis at a height corresponding to the suprasternal notch (the point A).



FORCES ACTING ON A PRONE SUBJECT EQUIPPED WITH A PERSONNEL FLOTATION DEVICE - HEAD FLEXED
Figure 7

m	is the distance along the body axis from A to CG(0)
p	is the distance from the point A to $CV_o(\theta)$
$d_f(\theta)\mathrm{Sin}(\theta - \theta_f)$	is the horizontal distance from $CG(\theta)$ to $CV_T(\theta)$
θ_f	is the prone rotational equilibrium angle for the fully submerged subject with head flexed.
h	is the subject's height.
$\frac{h}{8}\sin\theta$	is the horizontal distance from CG(0) to $CG(\theta)$ (see Appendix D)

It is assumed that the head is flexed at an angle of 45° to the trunk axis and it is further assumed that all quantities shown as functions of θ may vary with θ.

If we now take moments about the point A, we obtain for a total moment acting on the subject

$$M_f(\theta) = \rho_w V_T d_f(\theta)\sin(\theta - \theta_f) + S\{m - \frac{h}{8}\}\sin\theta - 0.7p\{B(\theta) - S\}\{\cos\theta + \sin\theta\}$$

$$+ B(\theta)\ \{x(\theta)\cos\theta + y(\theta)\ \sin\theta\} \qquad (7)$$

Upon inspection, each of the terms in equation (7) can be associated with either the subject or the personnel flotation device.

$M(\theta)$	is defined as the total moment acting on the subject inclined at the angle θ with head flexed. If this quantity is positive, the subject in Figure 7 will be rotated in a counterclockwise direction from the prone position toward the supine position. When $M(\theta)$ is zero, he will be at equilibrium, and when negative, he will be rotated clockwise further into the prone position.
$\rho_w V_T d_f(\theta) \sin(\theta - \theta_f)$	is defined as the submerged moment and it is a function only of the physical characteristics of the subject and his orientation. It can be seen from equation (7) that if the subject were allowed to slowly sink in the prone position with $B(\theta) = 0$, i.e., no personnel flotation device and $S = 0$ due to the downward acceleration, neglecting viscous effects, then the total moment acting on the submerged subject would be the defined submerged moment.
$S\{m - \frac{h}{8}\} \sin \theta$	is defined as the submerged weight moment and again is a function only of the physical characteristics of the individual and his orientation.
$-0.7p\{B(\theta) - S\}\{\cos \theta + \sin \theta\}$	is defined as the floated volume moment since it is a function of the volume floated above water, i.e., $(B(\theta) - S)$, and the location of the center of buoyancy of this floated volume.

$B(\theta)\{x(\theta)\cos\theta + y(\theta)\sin\theta\}$ is defined as the device moment since it is related only to the amount of buoyancy provided by the personnel flotation device and the location of its center of buoyancy.

Head Extended

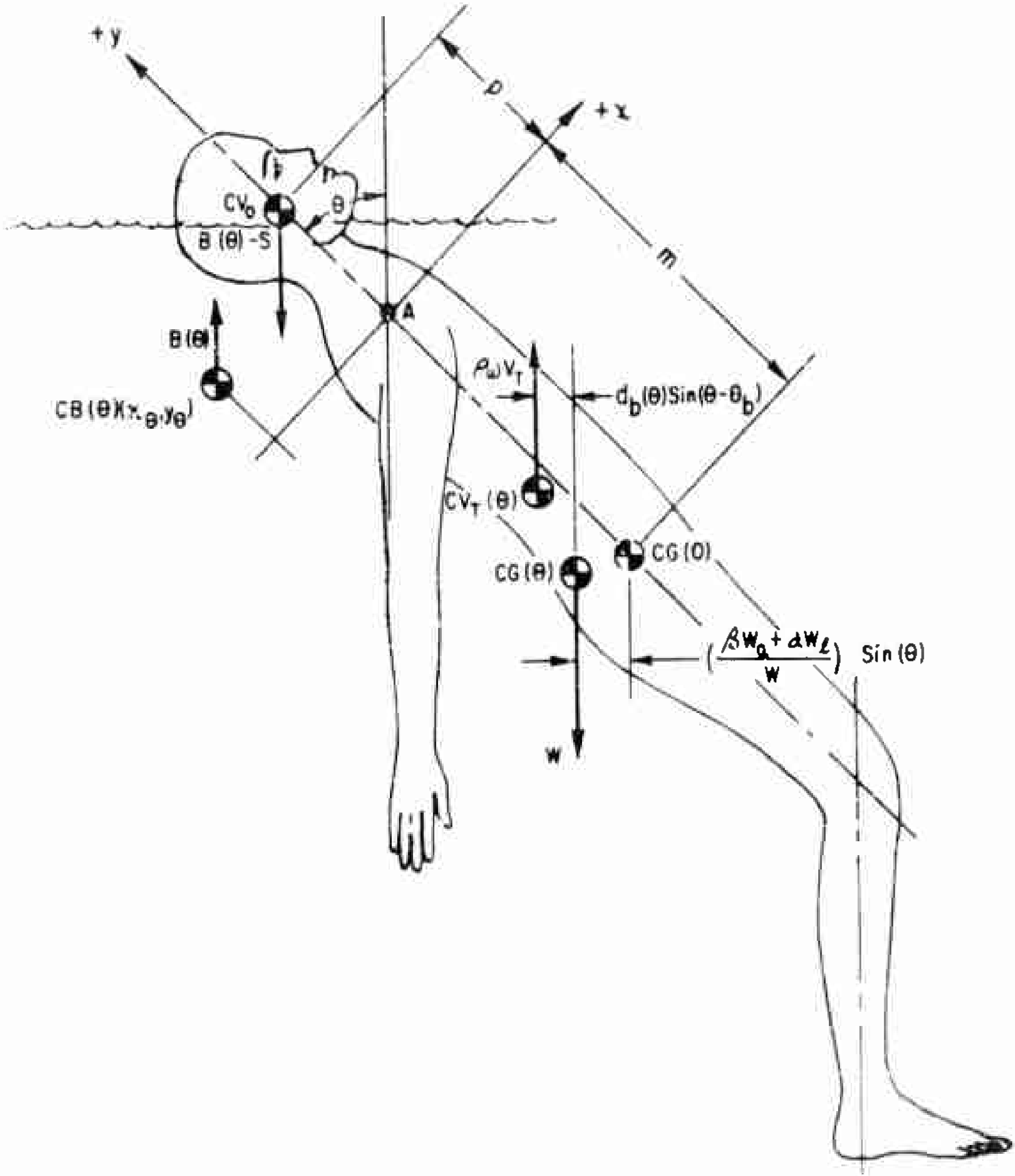
If we consider a subject in flotation equilibrium though not necessarily in rotational equilibrium in the supine position, we have the situation diagrammed in Figure 8, where all quantities are as previously defined with the exception of

θ_b is the supine rotational equilibrium angle for the fully submerged subject with head extended.

$d_b(\theta)\sin(\theta - \theta_b)$ is the horizontal distance from $CG(\theta)$ to $CV_T(\theta)$.

$\frac{\beta W_a + \alpha W_\ell}{W}\sin\theta$ is the horizontal distance from $CG(0)$ to the $CG(\theta)$ (see Appendix D)

It is assumed that the center of buoyancy of the floated volume when the head is extended is on the trunk axis a distance p above the point A.



FORCES ACTING ON A SUPINE SUBJECT EQUIPPED WITH A PERSONNEL FLOTATION DEVICE – HEAD EXTENDED

FIGURE 8

If we now take moments about the point A the total moment acting on the subject is given by

$$M_b(\theta) = \rho_w V_T d_b(\theta) \sin(\theta - \theta_b) + S\left\{m - \frac{\beta W_a + \alpha w_\ell}{W}\right\} \sin\theta + \{B(\theta) - S\} p \sin\theta$$
$$+ B(\theta)\{x(\theta)\cos\theta + y(\theta)\sin\theta\} \qquad (8)$$

Upon inspection, each of the terms in equation (8) can be associated with either the subject or the personnel flotation device.

$M(\theta)$	is defined as the total moment acting on the subject inclined at the angle θ with head extended. If this quantity is positive the subject in Figure 8 will be rotated in a counterclockwise direction, i.e., further in the supine direction. When $M(\theta) = 0$ he will be at equilibrium, and when negative, he will be rotated toward the prone position.
$\rho_w V_T d_b \sin(\theta - \theta_b)$	is defined as the <u>submerged moment</u> and is a function only of the physical characteristics of the individual and his orientation.
$S\left\{m - \frac{\beta W_a + \alpha W_\ell}{W}\right\}\sin\theta$	is defined as the <u>submerged weight moment</u> and is a function only of the physical characteristics of the individual.
$\{B(\theta) - S\}\ p \sin\theta$	is defined as the <u>floated volume moment</u>. It is a function of the volume floated above water and the location of the center of buoyancy of this volume.

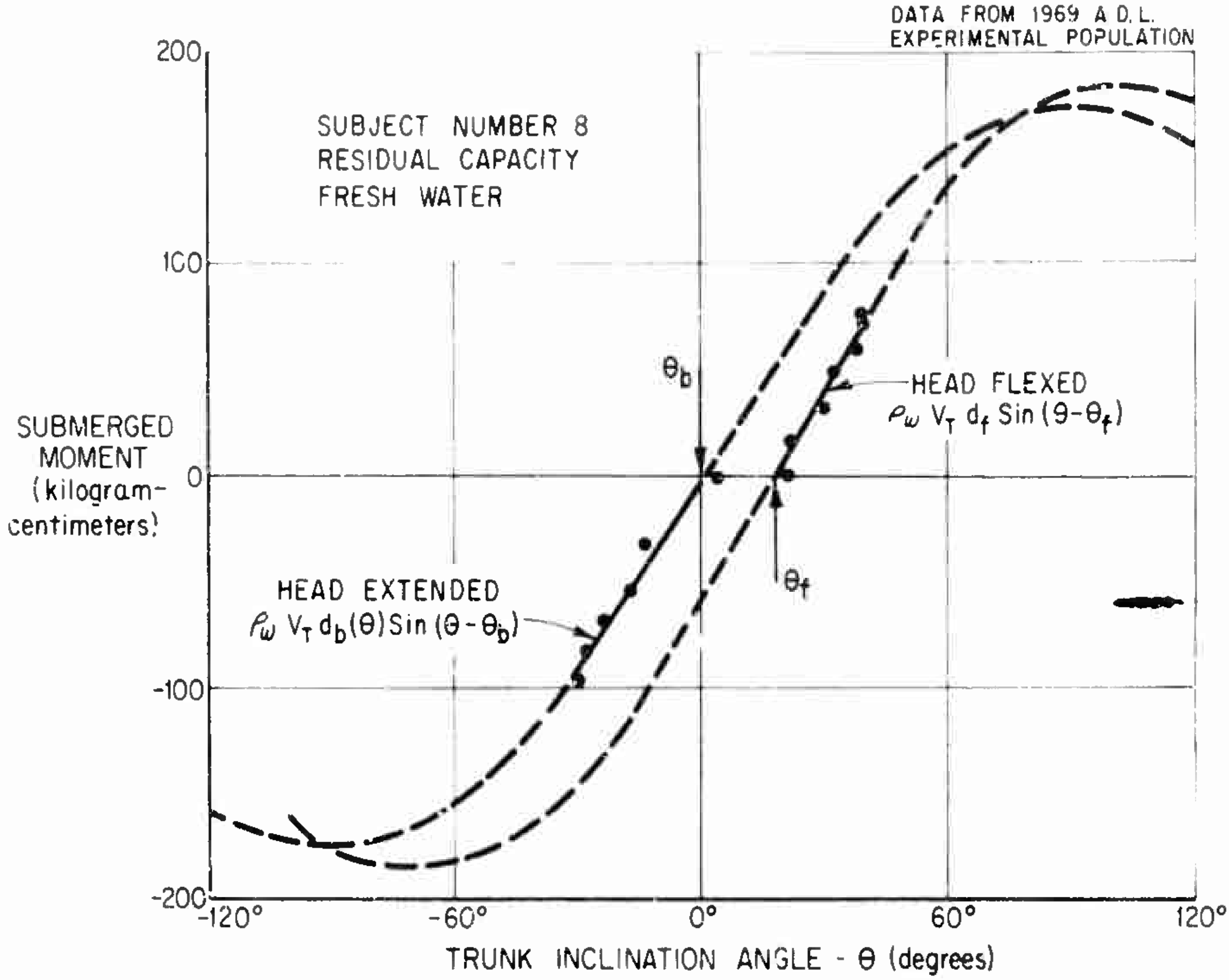
$B(\theta)\{x(\theta)\cos\theta + y(\theta)\sin\theta\}$ is defined as the device couple since it is a function only of the buoyancy provided by the personnel flotation device and the location of its center of buoyancy.

Application of Theory

The quantities in equations (7) and (8) relating to the individual subject's physical characteristics have been measured for each of the limited sample of subjects with the exception of the quantity $\beta W_a + \alpha W_\ell$. However, this quantity can be estimated to within the required accuracy for present purposes from general anthropometrical statistical data.

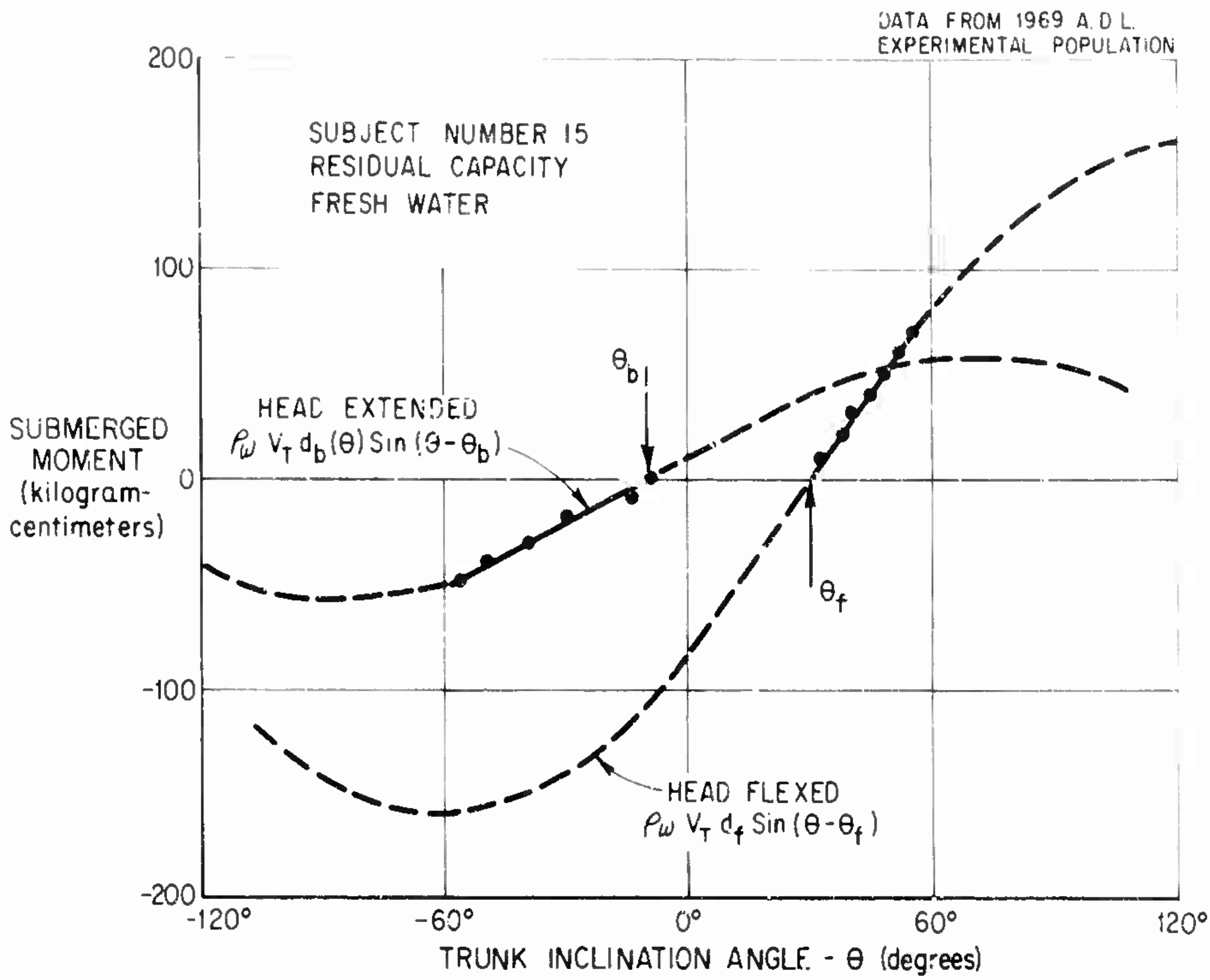
The functions $\rho_w V_T d_f(\theta) \sin(\theta - \theta_f)$ and $\rho_w V_T d_b(\theta) \sin(\theta - \theta_b)$ have been measured directly by applying couples of known magnitude to the fully submerged subjects, and measuring the new equilibrium angles when the lungs were expired to residual volume. Measurements on typical subjects are shown in Figures 9 and 10. These functions were not experimentally measured over the full range of physical interest. Therefore, for the present analysis, it is necessary to extrapolate the sinusoidal variation of these functions by not more than a maximum of 30° from their zero point to evaluate device performance near vertical, and by not more than 45° to evaluate device performance at -90°.

The equilibrium angles θ_f and θ_b, the submerged weight, S, at residual lung volume and subject's height, h, were measured directly. The distance from the height of the suprasternal notch to the erect center of gravity, m, was derived from the anthropometrical measurements and general



EXPERIMENTALLY MEASURED SUBMERGED MOMENT FOR AN ADULT MALE- LUNGS AT RESIDUAL CAPACITY (SINUSOIDAL EXTRAPULATIONS ASSUME d CONSTANT)

Figure 9



EXPERIMENTALLY MEASURED SUBMERGED MOMENT FOR AN ADULT FEMALE – LUNGS AT RESIDUAL CAPACITY (SINUSOIDAL EXTRAPULATIONS ASSUME d CONSTANT)

Figure 10

statistical data. The distance, p, from the height of the suprasternal notch to the center of buoyancy of the floated volume is assumed to be equal to the measured distance from the suprasternal notch to the external meatus when the subject is erect. This distance has been measured on each of the subjects.

Within the context of the noted assumptions, approximations and extrapolations to the existing data on the limited experimental population, we have a sufficiently complete data set to use as an illustration of the statistical methods that can be applied to evaluate the stability provided by a personnel flotation device providing a known amount of buoyancy and known moments as a function of trunk inclination angle. Alternatively, we can specify the buoyancy and the moments that must be supplied to each subject to assure that he will be:

- floated with sufficient freeboard
- rotated from the prone to the supine position
- not be rotated from the supine to the prone position
- find a supine equilibrium position at $\theta > -90^{\circ}$

1. Proper Rotation from Prone Equilibrium

Referring to equation (7), if it is desired to effect an initial rotation from the submerged equilibrium angle θ_f toward the vertical, it is necessary that the total moment be positive. Under this condition:

$$M_f(\theta_f) = S\left\{m - \frac{h}{8}\right\} \sin \theta_f - 0.7p\,\{B(\theta_f) - S\}\{\cos \theta_f + \sin \theta_f\}$$

$$+ B(\theta_f)\{x(\theta_f) \cos \theta_f + y(\theta_f) \sin \theta_f\} > 0 \qquad (9)$$

Therefore,

$$x(\theta_f) + y(\theta_f) \tan \theta_f > 0.7p \left\{1 - \frac{S}{B(\theta_f)}\right\} \left\{1 + \tan \theta_f\right\}$$

$$- \frac{S}{B(\theta_f)} \left\{m - \frac{h}{8}\right\} \ldots \theta_f \tag{10}$$

Inequality (10) relates the coordinates of the center of buoyancy of $B(\theta_f)$ to the physical dimensions of the subject and his submerged weight S. By inspection, it is seen that the distances to the center of buoyancy of $B(\theta_f)$ can be minimized by minimizing $B(\theta_f)$. It is also seen that those subjects with larger values of S require the smaller values of x and y to satisfy the criteria for proper rotation from prone equilibrium.

The inequality (10) establishes a criteria for choosing the value of $x(\theta_f) + y(\theta_f) \tan \theta_f$. It does not provide a method of choosing x and y independently. To do this, it is necessary to consider rotation through the vertical from the prone to supine orientation.

2. Rotation Through Vertical, Prone-to-Supine

Referring to equation (7), if it is desired to assure rotation through vertical from the prone to the supine orientation, it is necessary that the total moment be positive at $\theta = 0$. Under this condition:

$$M_f(0) = \rho_w V_T d_f \sin(-\theta_f) - 0.7 \left\{B(0) - S\right\} p + B(0)\, X(0) > 0 \tag{11}$$

Therefore,

$$x(0) > 0.7 \left\{1 - \frac{S}{B(0)}\right\} p - \frac{\rho_w V_T d_f}{B(0)} \sin(-\theta_f) \tag{12}$$

3. No Rotation Through Vertical Supine-to-Prone

Referring to equation (8), it is necessary to assure that there shall be no rotation through vertical from the supine-to-prone orientation. To assure this, it is necessary that

$$M_b(0) = \rho_w V_T d_b \sin(-\theta_b) + B(0)\, X(0) > 0 \tag{13}$$

Therefore,

$$x(0) > -\frac{\rho_w V_T d_b}{B_o} \sin(-\theta_b) \tag{14}$$

4. Supine Equilibrium at $\theta > -90^\circ$

Referring to equation (8) it is necessary to assure that the supine equilibrium occurs at $\theta_b > -90^\circ$. To accomplish this, it is necessary that

$$M_b\left(-\frac{\pi}{2}\right) = \rho_w V_T d_b \left(-\frac{\pi}{2}\right) \sin\left(-\frac{\pi}{2} - \theta_b\right) - S\left\{m - \frac{\beta W_a + \alpha W_\ell}{W}\right\}$$

$$- \left(B\left(-\frac{\pi}{2}\right) - S\right) p - B\left(-\frac{\pi}{2}\right) y\left(-\frac{\pi}{2}\right) < 0 \tag{15}$$

On our limited sample, the average supine equilibrium angle $\theta_b = -3^\circ$ for adult females with a variance $\sigma_{\theta_b} = 7^\circ$, and for adult males $\theta_b = -3^\circ$ with a variance of -5°. In the extreme case, the maximum value for θ_b will be of the order of -15°. The $\sin\left(-\frac{\pi}{2} - [-15^\circ]\right) = \sin -75^\circ = -.96$. We can then to good approximation in equation (15) let $\sin\left(-\frac{\pi}{2} - \theta_b\right) = -1.0$, and it therefore follows that:

$$y\left(-\frac{\pi}{2}\right) > -\frac{\rho_w V_T d_b\left(-\frac{\pi}{2}\right)}{B\left(-\frac{\pi}{2}\right)} - \frac{S}{B\left(-\frac{\pi}{2}\right)}\left\{m - \frac{\beta W_a + \alpha W_\ell}{W}\right\} - \left(1 - \frac{S}{B\left(-\frac{\pi}{2}\right)}\right)p \tag{16}$$

EXAMPLE WITH FIXED BUOYANCY

At this time, detailed calculations of the effectiveness of a PFD with a fixed amount of buoyancy at a fixed location with respect to the subject have been carried on for one value of buoyancy, namely, 26 pounds. This is perhaps an upper limit that would be provided by an effective PFD as influenced by wearability considerations. The methods employed however are equally applicable to cases where less buoyancy is provided.

It is assumed for the sake of this illustration that the statistical curves in this report faithfully represent the characteristics of the adult male and female boating population. The method of applying the formalism developed in the previous sections is as follows.

BUOYANCY

- The adequacy of the buoyancy provided by the PFD is evaluated by use of the statistical curves shown in Figures 5 and 6, on pages 28 and 29.

Referring to these two figures, and considering two personnel flotation devices, one providing 15 pounds of buoyancy, and one providing 26 pounds of buoyancy, we obtain the results shown in Tables I and II for the fraction of the population floated with indicated volumes above water under different conditions of inflation of the lungs.

Volume Above Water	ADULT MALE		ADULT FEMALE	
	Head Plus Neck	Head Alone	Head Plus Neck	Head Alone
Residual Lung Volume	0%	40%	22%	> 99%
Functional Residual Lung Volume	22%	92%	90%	> 99%

TABLE I PERCENT OF POPULATION FLOATED WITH INDICATED VOLUME OR GREATER ABOVE WATER AT INDICATED LUNG VOLUME FOR A PFD PROVIDING 15 POUNDS OF BUOYANCY

Volume Above Water	ADULT MALE		ADULT FEMALE	
	Head Plus Neck	Head Alone	Head Plus Neck	Head Along
Residual Lung Volume	90%	> 99%	> 99%	> 99%
Functional Residual Volume	> 99%	> 99%	> 99%	> 99%

TABLE II PERCENT OF POPULATION FLOATED WITH INDICATED VOLUME OR GREATER ABOVE WATER AT INDICATED LUNG VOLUME FOR A PFD PROVIDING 26 POUNDS OF BUOYANCY

From Table I it is seen that the <u>15</u> pounds of buoyancy is adequate to float greater than 99% of the adult female population with the volume of their head above water under all conditions of lung inflation. It is in fact adequate to float 92% of the adult male population with the volume of the head above water at normal lung volume (i.e., functional residual lung volume). It is seen, however, if in the case of adult males, that if the lung volume is decreased or the volume to be floated above water is increased from that of the head alone to that of the head plus neck, that there is a sharp drop in the fraction of the population so floated.

In Table II, where we consider <u>26</u> pounds of added buoyancy, it is seen that greater than 99% of both the adult male and female population will be floated with the volume of the head and neck above water with one exception, that is, when the adult male fully exhales until his lungs are deflated to residual volume. Even under these conditions, 90% of the adult male population will be floated with a volume equal to or greater than that of the head plus neck above water. It is from this type of analysis, carried out in detail on a statistically reliable set of data, that one can establish measures of effectiveness for the added buoyancy provided by a personnel flotation device. On the assumption that the present data represent the general population, one can judge that with respect to buoyancy alone that 15 pounds might be adequate for adult females but that it might be marginal for adult males. One tne other hand, 26 pounds of added buoyancy appears to be more than adequate for all cases except the extreme case of the adult male at minimum lung volume, and floated volume equal to or greater than that of the head plus neck.

STABILITY

- The stability provided by a personnel flotation device of fixed buoyancy is a function only of the location of the center of buoyancy of the PFD relative to the subject. To be judged as adequate in the present context, the location of the center of buoyancy of the device must be such that:

  1. The subject is initially rotated toward the vertical from the prone equilibrium position without a PFD. (Inequality (10), page 42)
  2. The subject is rotated through vertical from the prone to the supine position when the head is flexed (Inequality (12), page 42)
  3. The subject has a supine equilibrium position at an angle that is less than -90° so that his nose and mouth remain above water. (Inequality (16), page 43)

It turns out that the second condition above is a condition only on the horizontal distance (X) from the center of buoyancy of the PFD to the centerline of the subject's body and is independent of its location vertically on the chest. Having established this distance it is then possible to evaluate the first and third conditions with respect to which is the more stringent on vertical placement (Y) of the PFD.

Using the referenced inequalities and the data from the experimental measurements made on each of the individuals in the statistical population sample, calculations must be performed for each individual and the final results analyzed statistically. Since there is a large amount of repetitive calculation required, a computer program has been written to solve the three inequalities (10), (12) and (16). The data for each subject are read into the computer. It then calculates the required horizontal distance (X) from that subject's body centerline to the center of buoyancy of the PFD and the maximum allowable vertical distance (Y) from the top of the breast bone (suprasternal notch) to the center of buoyancy of the PFD. The computer program is listed and the calculations for the 26 pound added buoyancy case are shown in Appendix B.

After the individual calculations are completed, the results are treated statistically in terms of the fraction of the population that will be adequately served in terms of proper rotation and equilibrium defined by the three conditions outlined above. The statistical results for the location of the center of buoyancy of the PFD for the 26 pound added buoyancy case are shown in Figures 11, 12 and 13.

Figure 11 gives the fraction of the population that will be rotated through vertical from the prone to the supine position for a given value of the horizontal distance (X) from the body centerline to the center of buoyancy of the PFD. If, for example, a PFD provides 26 pounds of buoyancy and the center of buoyancy is six inches from the body centerline, then 32% of the adult female population and 70% of the adult male population will be rotated through vertical.

Figures 12 and 13 both relate to the vertical location of the center of buoyancy of the PFD with respect to the top of the breastbone (suprasternal notch). The result in Figure 12 is based on the assumption that the PFD provides 26 pounds of buoyancy and thet its center of buoyancy is 10.2 inches from the body centerline. The result in Figure 13 is based only on the assumption that the PFD supplies 26 pounds of buoyancy and is independent of the horizontal distance (X) as seen in inequality (16).

Figure 12 represents the fraction of the population having an initial rotation toward vertical, while Figure 13 represents the fraction of the population having a supine equilibrium that is at less than -90°. In comparing these two curves that the more stringent condition is imposed by the supine equilibrium condition, Figure 13, for all but the highest percentage of population cases. As a result, we find from Figure 13 that if the center of buoyancy of the PFD is 9 inches below the top of the breastbone (suprasternal notch) that only 40% of the adult female population will be rotated toward vertical from -90°, while 80% of the adult male population will be rotated toward vertical from this position.

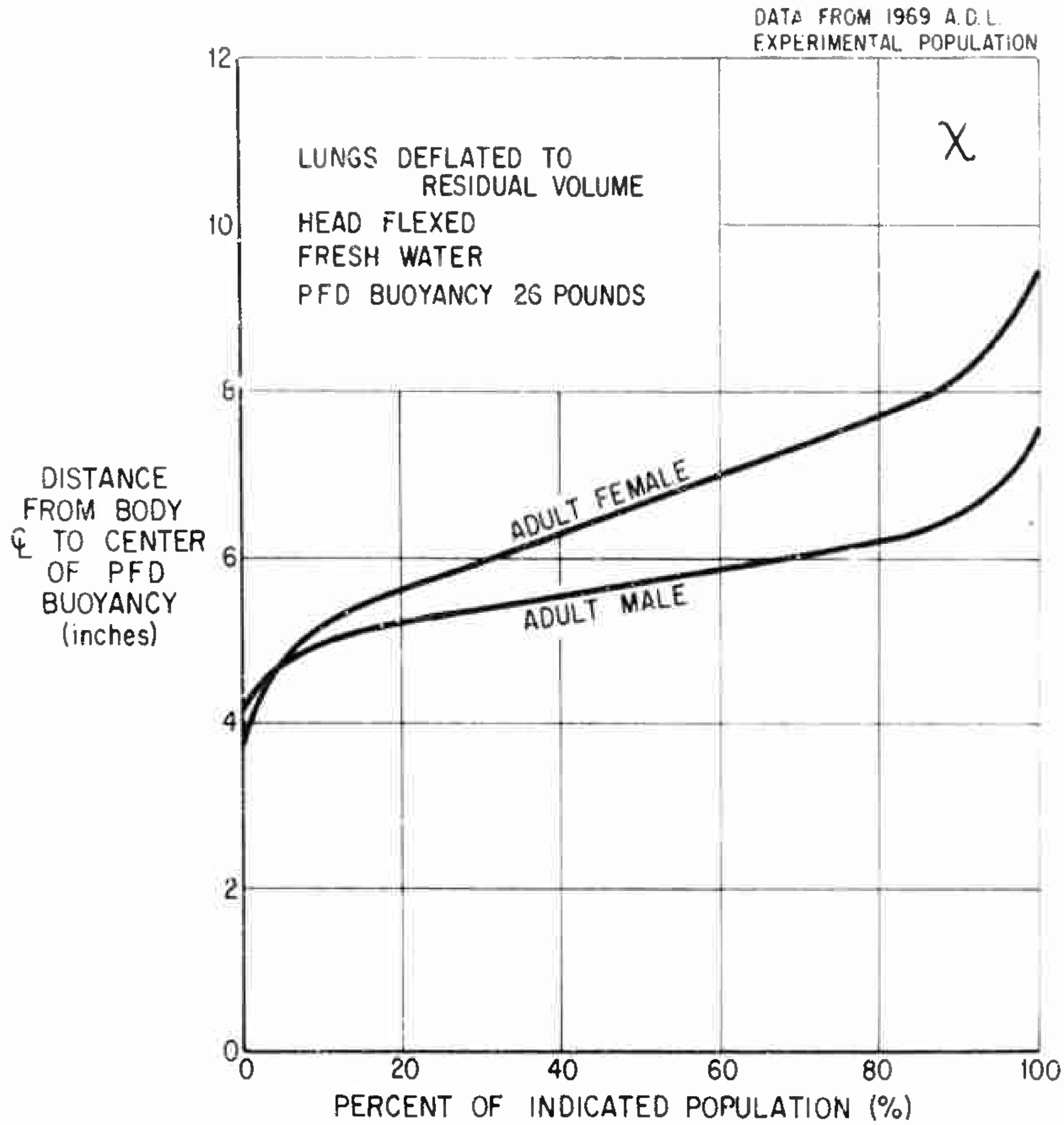
CONCLUSION

Repeating these types of calculations for varying amounts of buoyancy and different centers of buoyancy for the PFD, we can for each combination calculate the following:

1. From Figures 4 and 5, the fraction of the population that will be floated with head or head plus neck volume above water for varying lung volume.
2. From figures similar to Figure 12 for varying amounts of added buoyancy and different horizontal and vertical distances to the PFD center of buoyancy, the fraction of the population that will have the proper initial rotation from the prone position.
3. From figures similar to Figure 13 for varying amounts of added buoyancy and different vertical distances to the PFD center of buoyancy, the fraction of the population that will be rotated toward vertical from -90° (i.e., have an acceptable supine equilibrium position).

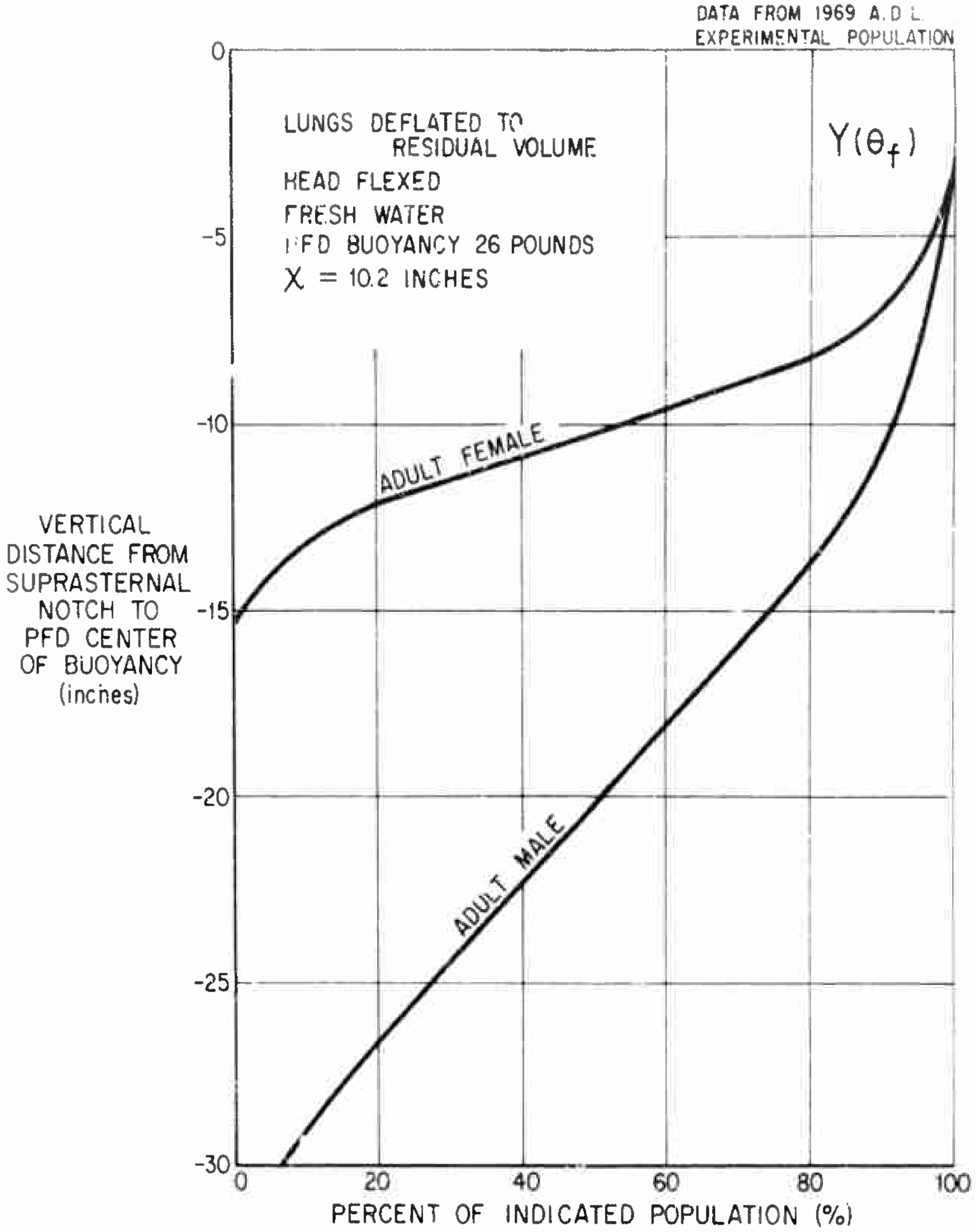
It should be emphasized at this point that the present treatment of buoyancy and stability is based on experimental data from a limited population obtained at residual lung volume. The statistical uncertainty in the data has been noted earlier. Through measurement of expiratory reserve capacity, the results on buoyancy requirements can be stated at normal lung volume (i.e., functional residual capacity). The preceding discussion on stability requirements has been with reference to the lungs at residual volume (i.e., fully expired) rather than at normal lung volume. The effect of this change in lung volume has

not as yet been evaluated. However, on the basis of the experimental data on measured lung volumes and anthropometric data that effect of this change can be calculated. It may also be possible to measure the effect of this change experimentally; however, this has not as yet been done.



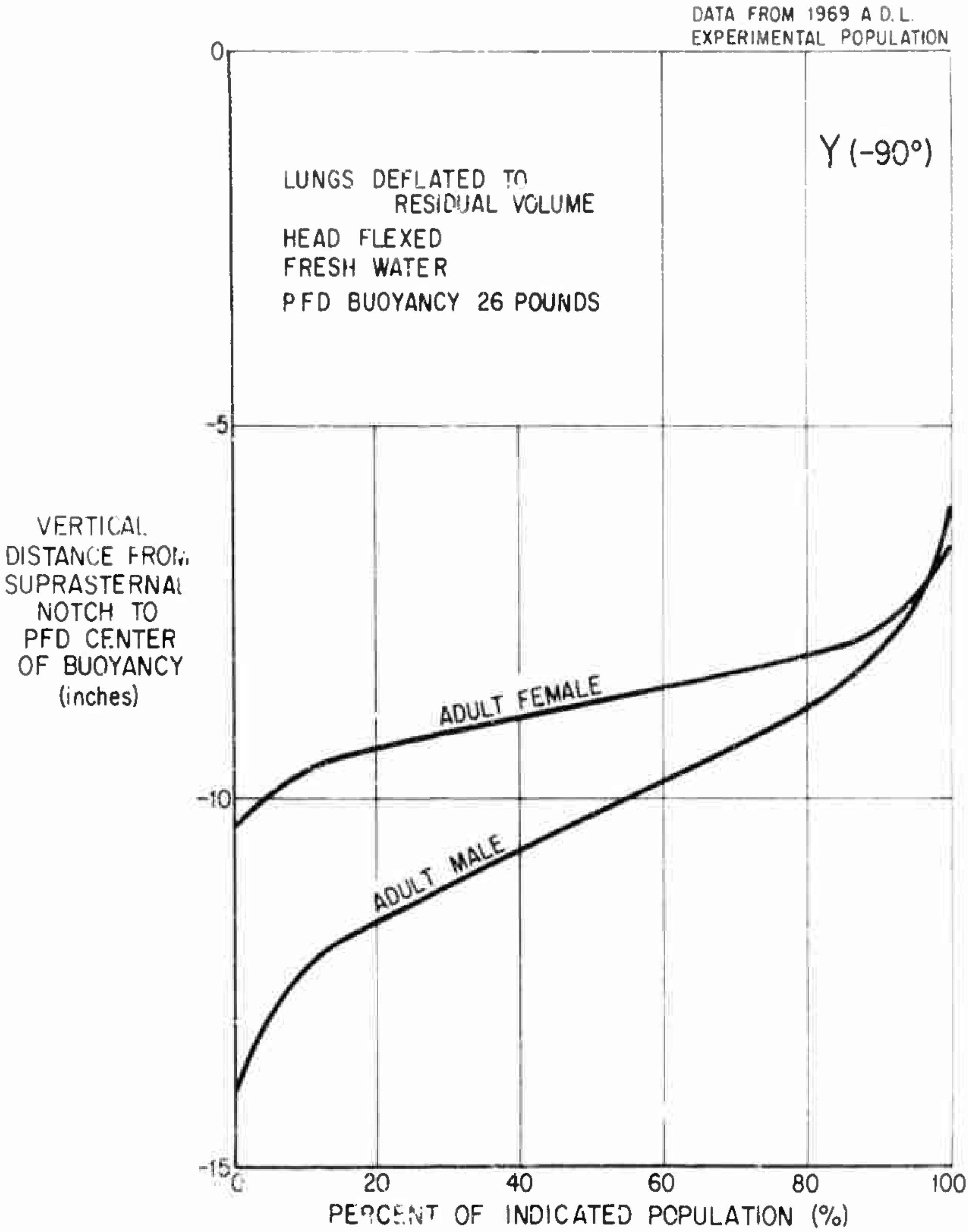
PERCENT OF INDICATED POPULATION ROTATED THROUGH VERTICAL FROM THE PRONE TO THE SUPINE POSITION VS. DISTANCE FROM BODY CENTERLINE TO PFD CENTER OF BUOYANCY

Figure 11



PERCENT OF INDICATED POPULATION ROTATED TOWARD VERTICAL FROM PRONE EQUILIBRIUM AS A FUNCTION OF VERTICAL LOCATION OF PFD CENTER OF BUOYANCY

Figure 12



PERCENT OF INDICATED POPULATION ROTATED TOWARD VERTICAL FROM $\theta = -90°$ VS. VERTICAL LOCATION OF PFD CENTER OF BUOYANCY

Figure 13

MEASUREMENT PRECISION AND SAMPLE SIZE REQUIREMENTS

It is planned to use data obtained from a series of experiments, performed on a randomly selected population sample, to statistically determine the adequacy of the buoyancy and stability provided by personnel flotation devices of varying design. These devices must be adequate to serve the requirements of a major fraction of the population, therefore it is not sufficient to establish only the mean requirement, but it is also necessary to predict the variance of the individual requirements. If both the mean and the variance are estimated, then it is possible to make meaningful estimates of the requirements of the extremes of the population rather than only the requirements of the mean individuals.

MEASUREMENT PRECISION

In any statistical measurement experiment on a distributed physical characteristic, there are two factors that are of importance. These are: the actual distribution of the characteristic over the population, and the undertainty in the measurement of the characteristic on a single subject. These two factors combine to give a final result that combines the two factors. If $\bar{X}$ is the average value and σ_x is the average value for the variance physical characteristic, and $\bar{Y}$ is the average value for the error, and σ_y is the average value for the variance in the error in the measurement of the characteristic of a single individual, then the experimentally observed distribution will have the following characteristics.

$$\bar{Z} = \bar{X} + \bar{Y} \qquad (1)$$

$$\sigma_z = \{\sigma_x^2 + \sigma_y^2\}^{\frac{1}{2}} \qquad (2)$$

where $\bar{Z}$ is the experimentally determined mean value, and σ_z is the experimentally determined variance.

However, if $\sigma_y < \sigma_x$, then

$$\sigma_z = \sigma_x \left\{1 + \frac{\sigma_y^2}{\sigma_x^2}\right\}^{\frac{1}{2}} = \sigma_x \left\{1 + \frac{1}{2}\frac{\sigma_y}{\sigma_x}\right\} + 0\left(\frac{\sigma_y}{\sigma_x}\right)^2 \qquad (3)$$

Therefore

$$\sigma_z > \sigma_x \left\{1 + \frac{1}{2}\frac{\sigma_y}{\sigma_x}\right\} \qquad (4)$$

Equation (1) states that the mean value of the experimentally determined distribution is biased from the characteristic distribution by the mean value of any systematic error that one makes in measurement on an individual. Equation (4) states that the variance obtained in the experimental distribution is increased by one half the ratio of the measurement variance to the characteristic variance. That is, the experimental variance will be larger than the characteristic variance.

In our measurements program it is reasonable to assume that there is no systematic error in the individual measurements, that is $\bar{Y} = 0$ and further, it can be assumed in each case that the variance of the individual measurements is small compared to the variance of the characteristic. Typically, in the case of the measurement of submerged weight of adult females, shown in Figure 4 , the experimentally measured

distribution has a mean value of approximately $\bar{Z} = 4.0$ pounds with $\sigma_z = 0.5$ pounds. The variance, σ_y, in measurements on a single individual, is of the order of 1 to 2 ounces or approximately 0.1 pound. It therefore follows from equation (4) that

$$\sigma_x < \sigma_z - \tfrac{1}{2}\sigma_y \tag{5}$$

$$\sigma_x \leq 0.50 - 0.05$$

$$\sigma_x \leq 0.45 \text{ pounds}$$

It therefore follows that using the experimental distribution without correcting for the small variance associated with the individual measurements provides an overestimate of the variance in the characteristic.

There are two observations to be made, 1) that the effect is small, and 2) that using too large a variance results in conservative estimate of the fraction of the population having a characteristic that is equal to or less than some arbitrarily selected value. For this reason, in the work done to date, we have not corrected for the variance associated with measurements of physical characteristics of individuals. This line of reasoning applies to the measurements of weights, volumes, linear dimensions and applied moments. In future work, it is planned to obtain the variance of measurements on single individuals so that the indicated correction can be made to the observed experimental distributions.

SAMPLE SIZE REQUIREMENTS

In addition to the uncertainties associated with the individual measurements that make up a sample data set for the determination of the statistical distribution of a physical characteristic over the sample, there is the question as to how well the characteristics of the sample represent the characteristics of the general population. Statistically, it is always possible to improve the correspondence between the mean value and variance of a characteristic determined from a randomly selected sample, and the mean value and variance of the characteristic of the general population by increasing the size of the randomly selected sample.

The statistical tool used to evaluate the correspondence between the sample and population means and variances as a function of sample size is the statistical concept of confidence interval.

We can calculate the probability, $1 - \alpha$, that the mean value, μ, of the population is within a given interval about the sample mean value $\bar{x}$, determined from an experiment on n individuals. This is accomplished by using the sample variance s and the student "t" distribution[11] through the relationship:

$$\text{Prob}\left[\bar{x} - \frac{st_{n,\frac{\alpha}{2}}}{\sqrt{n}} \leq \mu \leq \bar{x} + \frac{st_{n,\frac{\alpha}{2}}}{\sqrt{n}}\right] = 1 - \alpha \tag{6}$$

We can calculate the probability, $1 - \alpha$, that the variance, σ_x^2, of the general population characteristic, is within a given interval about the sample variance S_x^2 determined from an experiment on n individuals. This is accomplished using the χ^2 distribution[11] through the relationship:

$$\text{Prob}\left[\frac{ns^2}{\chi^2_{n,\frac{\alpha}{2}}} \leq \sigma_x^2 \leq \frac{ns^2}{\chi^2_{n,1-\frac{\alpha}{2}}}\right] = 1 - \alpha \tag{7}$$

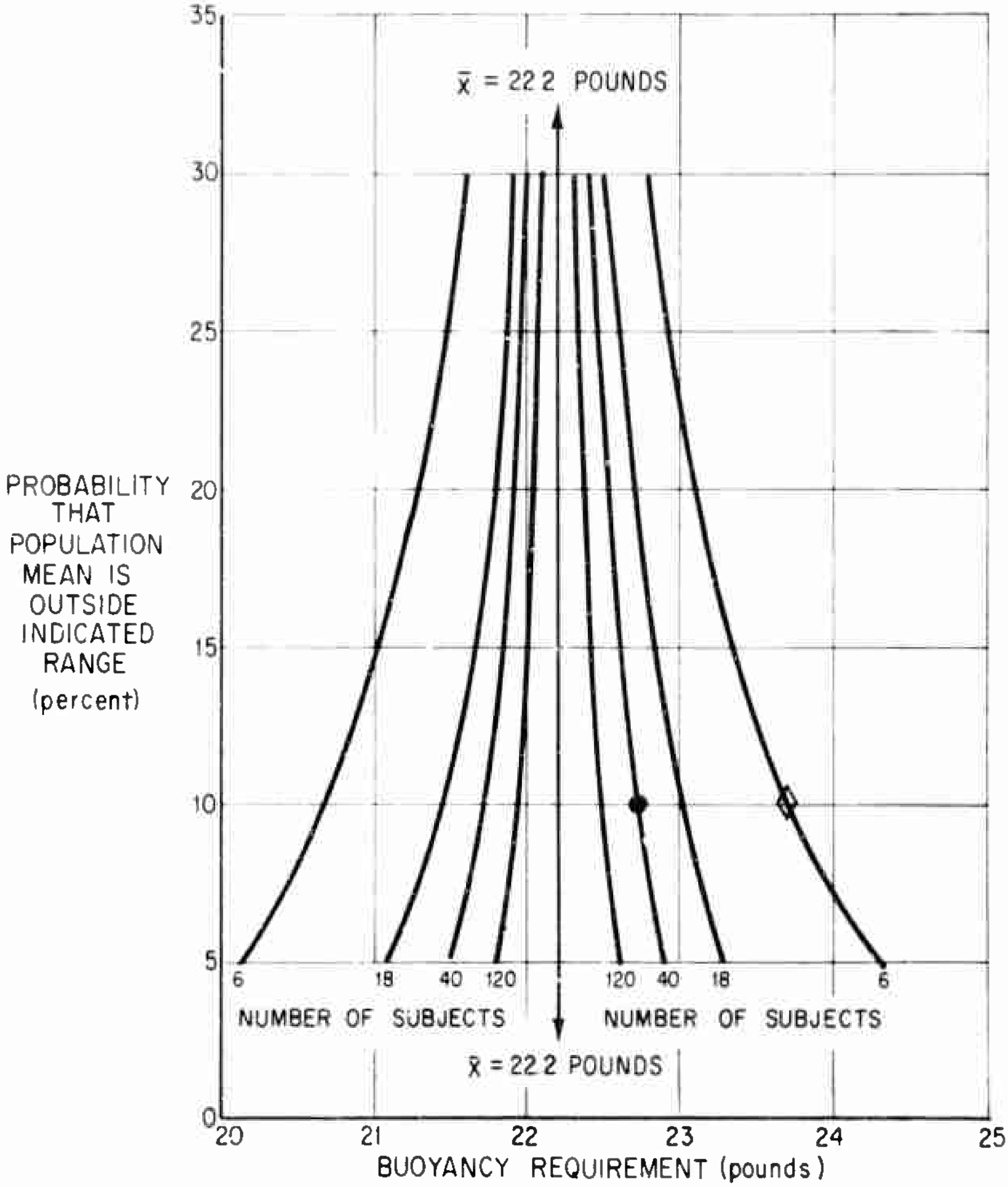
Consider the case in which the added buoyancy required to float adult males with a volume equivalent to that of the head plus neck above water with lungs expired to residual volume was determined. In the experiments on the 1969 ADL limited population, it was found that for data from seven subjects (n = 6) that the mean value of the buoyancy required was $\bar{x}$ = 22.2 pounds, and the sample variance was S_x^2 = 6.8 pounds squared. If the same result for $\bar{x}$ and S_x^2 were obtained from samples of larger size, it is possible to calculate the statistical probability that the mean value and variance in the general population

is outside a given range about the sample mean and variance. The results of these calculations for a sample mean of 22.2 pounds, and a sample variance of 6.8 pounds squared as a function of sample size are shown in Figures 14 and 15, respectively.

As an example of the use of these two curves, consider the results obtained for our limited sample of seven subjects with a sample mean of 22.2 pounds and a standard deviation of 2.6 pounds. The 98th percentile individual on the high end of the distribution is 2 sigma from the mean. His buoyancy requirement will be 22.2 + 2 x 2.6 or 27.4 pounds.

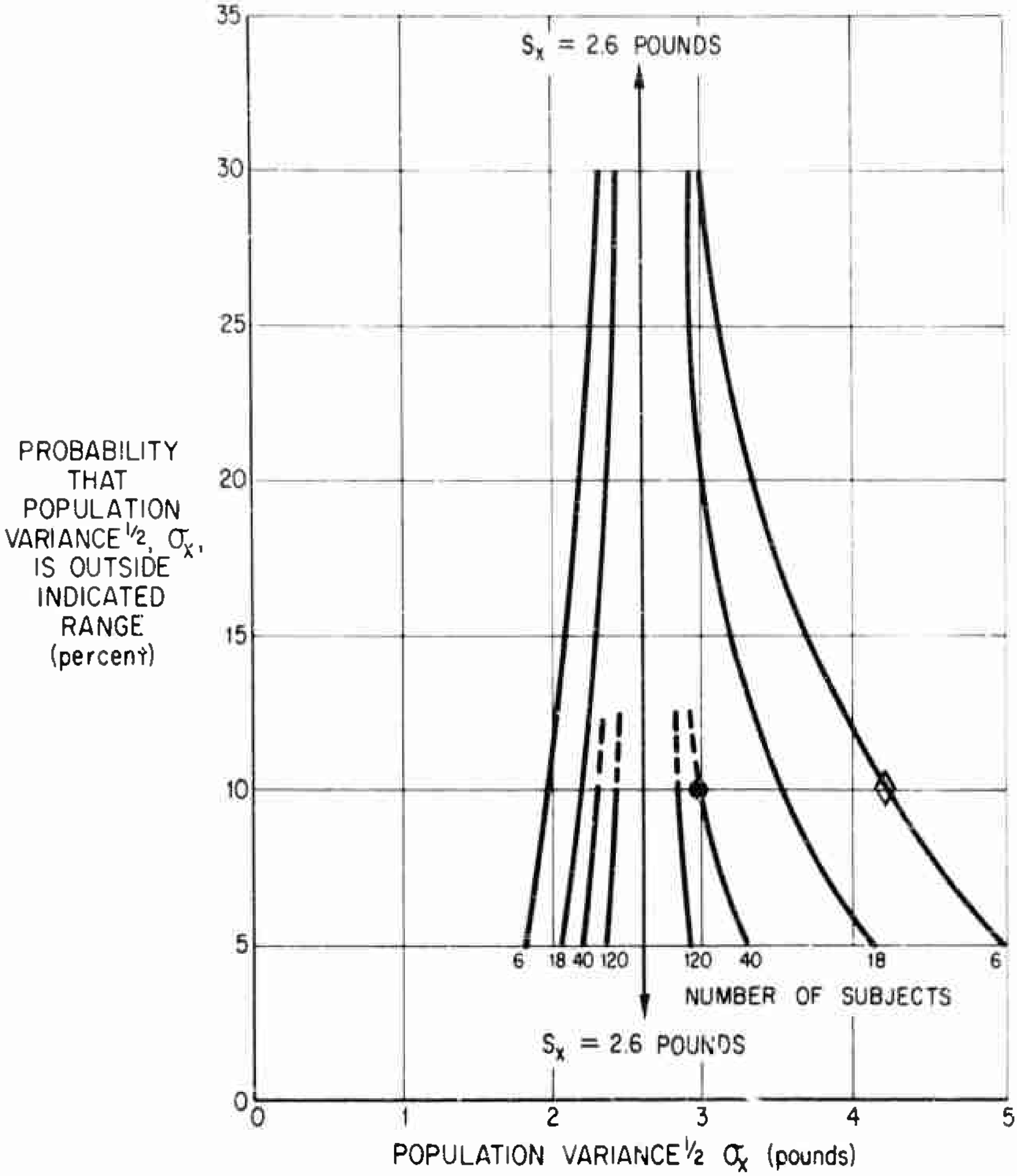
From Figures 14 and 15, we observe that if this mean and variance are determined with n = 6, then there is one chance in ten that for the general population that the mean is greater than 23.7 pounds, and one chance in ten that the standard deviation is greater than 4.2 pounds (indicated by a $\Diamond$ in each figure). It therefore follows that there is one chance in one hundred that the 98th percentile individual in the general population will require 32.1 pounds of buoyancy rather than the quoted 27.4 pounds.

If the mean and variance were obtained from an experiment employing forty subjects rather than seven, randomly selected from the general population, then we observe the following: There is one chance in ten that the mean value for the general population will be greater than 22.7 pounds and one chance in ten that the standard deviation will be greater than 3.0 pounds. It therefore follows that there is one chance in one hundred that the 98th percentile individual will require a buoyancy of 28.7 rather than the quoted 27.4 pounds.



PROBABILITY THAT THE MEAN VALUE OF THE BUOYANCY REQUIREMENT FOR THE GENERAL POPULATION FALLS OUTSIDE INDICATED RANGE ABOUT THE SAMPLE MEAN AS A FUNCTION OF SAMPLE SIZE

Figure 14



PROBABILITY THAT THE VARIANCE$^{1/2}$ FOR THE GENERAL POPULATION FALLS OUTSIDE THE INDICATED RANGE ABOUT THE SAMPLE VARIANCE

Figure 15

It follows that we can reduce the uncertainty in specifying the buoyancy requirement for the 98^{th} percentile individual from 4.7 pounds (~ 20%) to 1.3 pounds (~ 5%) at the 1% confidence limit by increasing our experimental sample from the general population from 7 people to 40 people. It is on this basis that we recommend a sample size of fifty subjects in each class for future statistical experiments designed to obtain basic data relating to buoyancy and stability requirements for the general boating population. A sample of this size will assure that the statistical distributions obtained reflect the distribution of the measured physical characteristics of the general population rather than the statistical uncertainties associated with the sampling procedures.

EXPERIMENTAL METHODS

SUBJECTS

One of the aims and objectives of the study was related to the ability of PFD's to serve as large a percentage of the population as possible and a statistical approach to the problem is required. Therefore, subjects were chosen on a 3 x 3 matrix consisting of tall, medium, short in one dimension and thin, muscular, fat in the other dimension with male and females in each of the 9 resulting cells. In this way it was hoped that we would be able to span the variations in the measures of interest comparable to the span found in a statistically valid population. The dimensions of tall, medium and short were obtained from published studies on height using the ranges of below the 25th percentile for short, of 45th to the 55th percentile for medium and the range above the 75th percentile for tall. The dimension of thin, muscular and fat was based upon an arbitrary selection of one of the investigators. Complete data were obtained on eight male and seven female subjects and as will be seen later, comparisons of the distribution of our subjects with existing data on large numbers of adult males and females in the United States showed that our sample fairly represented the U.S. general population reported by several investigators. (See Tables III and IV)

ANTHROPOMETRIC MEASUREMENTS

Anthropometric measurements were made according to standard methods used by most workers in this field. Any departures from standard methods were based upon our specific requirements with the consraint that all measurements were to be made to fixed and easily identifiable bony structures. For instance, where the bottom of the knee cap and the acromion process were used by some workers, this study used the top of the fibula and the sternal notch, respectively. It was found that the sternal notch was 0 - 1 inch lower than the acromion process and the bottom of the knee cap with the muscles relaxed was virtually the same as the top of the fibula. This is a stable reference point unaltered by changes in muscle tone.

The anthropometric measurements made were:

- body weight in swimming shorts for men and bathing suits for women.
- height in bare feet
- height to top of fibula
- crotch height
- iliac crest height
- xiphisternum height
- suprasternal notch height
- distances from suprasternal notch to the external meatus with head in the fully extended, fully flexed and vertical positions.

VOLUMETRIC MEASUREMENTS

Volumetric measurements were made by the water displacement method using a specially constructed tank into which subjects were lowered to the reference points used for the anthropometric measurements. Measurements above the xiphisternum were made with the lungs fully deflated to residual volume and included the volume of the arms. Neck volume measurements were made between the suprasternal notch to the lower edge of the mandible (jawline) adjusted to the horizontal position. Head volumes were obtained from the jawline in the horizontal position to full submersion. (Figure 16)

For the sake of ease of presentation, the following conventions were followed for naming certain segmental volumes:

- Volume between the top of head and lower edge of mandible is referred to as head volume.
- Volume between the lower edge of the mandible and the sternal notch is referred to as neck volume. This volume also includes part of the shoulders and back.
- Volume between the sternal notch and xiphisternum is referred to as chest volume, but this also includes volume of the arms.
- Volume between the xiphisternum and the iliac crest is referred to as upper abdomen volume.
- Volume between iliac crest and crotch is referred to as pelvis volume.
- Lower leg volume includes volumes of feet.

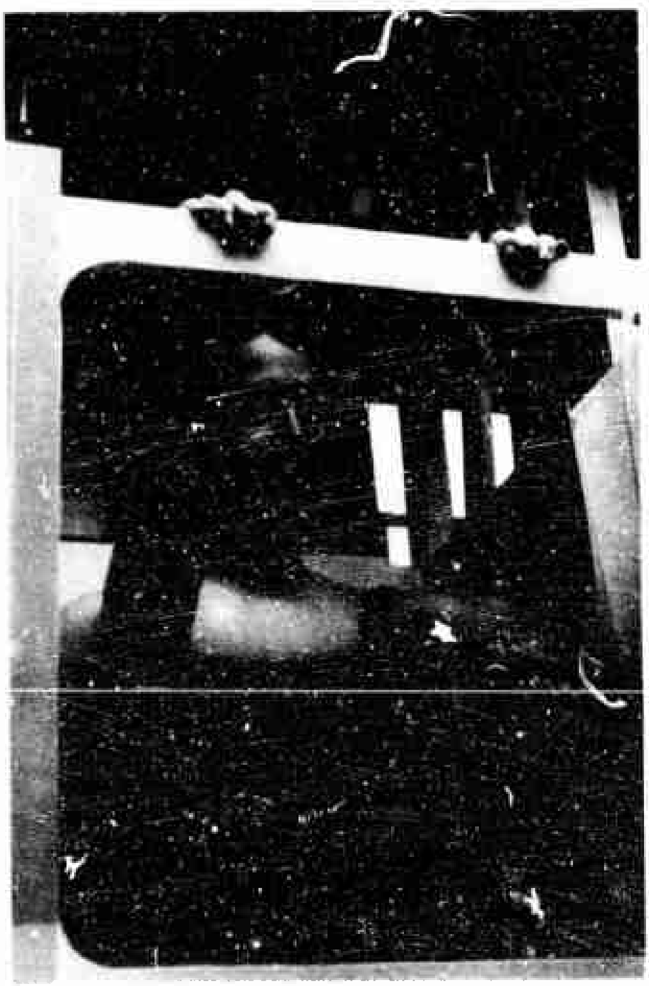


FIGURE 16

Two views of the tank for volumetric measurements and submerged weight determinations. Volume of anatomical segments are measured by incrementally lowering platform with subject into water. Submerged weight is obtained by adding a weighing scale suspended between the uppermost support beam and platform.

SUBMERGED WEIGHT

This was made in the same tank as was used for volumetric measurements. Subjects were weighed while fully submerged with lungs deflated to residual volume.

RESPIRATION MEASUREMENTS

These were made on each subject using a Thomas spirometer so that corrections could be made for various lung volume states and consisted of vital capacity, tidal volume, inspiratory capacity and expiratory reserve. Functional residual capacity is composed of maximum expiratory reserve plus residual volume, and results at this lung state can be calculated by adding expiratory reserve to the data which were obtained at residual volume. In like manner, results can be converted to total lung volume by adding vital capacity.

STABILITY MEASUREMENTS

The couple required to rotate the fully submerged subject to an arbitrary trunk inclination angle with head flexed and extended was measured using the apparatus shown in Figures 17 and 18. These measurements were performed in an indoor swimming pool. The device makes it possible to apply any desired couple to the subject without affecting his buoyancy. This was accomplished by adding a lead weight and an equal and opposite buoyant force to the horizontal arm. A close-up of the frame is shown in Figure 18. The lead weight, the buoyant material and the apparatus were adjusted to neutral buoyancy in fresh water. To the vertical arm was attached an antenna whose angle to the horizontal could be photographed directly. Using this apparatus, subjects

SUBJECT WEARING STABILITY MEASUREMENT FRAME

FIGURE 17

CLOSE-UP OF STABILITY MEASUREMENT FRAME DEPICTED IN FIGURE 1

FIGURE 18

assumed the angle imposed by the applied moment after having exhaled to residual volume. The antenna was photographed just before it disappeared below the surface of the water. The applied couple was computed from the known distance between the applied weight and applied buoyancy and the angle obtained from the photograph of the antenna.

TREATMENT OF DATA

Because subjects were selected to span the range of body shapes and sizes that might be found in the general adult population, the data were treated as representing a normal distribution for each of the characteristics measured. Accordingly, mean and variance were obtained and results illustrated either as cumulative plots to represent the probability that a characteristic is equal to or less than an indicated percentage of the adult population of males and females. Where appropriate points represented by the limited sample were included in the plots as either the male or female symbols.

Statistical analyses used the Snedecor's F test or variance ratio test for the statistical significance of the difference between the standard deviations of a given measurement. The student "t" test was used for the statistical significance of the difference between mean values of a given measurement. Significance was set at $p < 0.05$.

RESULTS

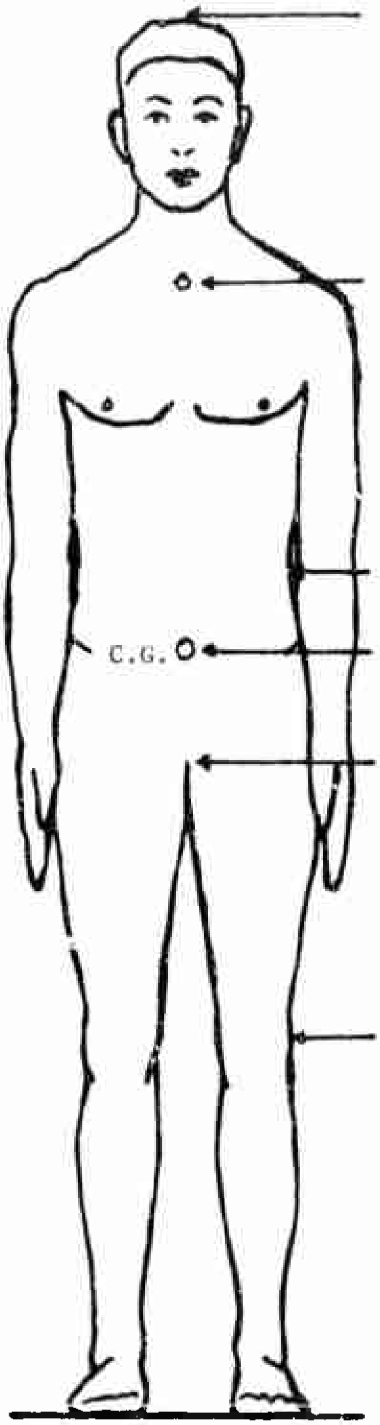
COMPARISON OF LIMITED SAMPLE WITH PUBLISHED STUDIES OF LARGE SAMPLES OF THE ADULT POPULATION

Of the adult 9 males and 9 females measured, complete and usable data were obtained on 7 male subjects and 6 female subjects. The anthropometric measurements were treated statistically to estimate mean values and variances of each of the following quantities:

- weight
- height of suprasternal notch
- height of iliac crest
- crotch height
- height of top of fibula

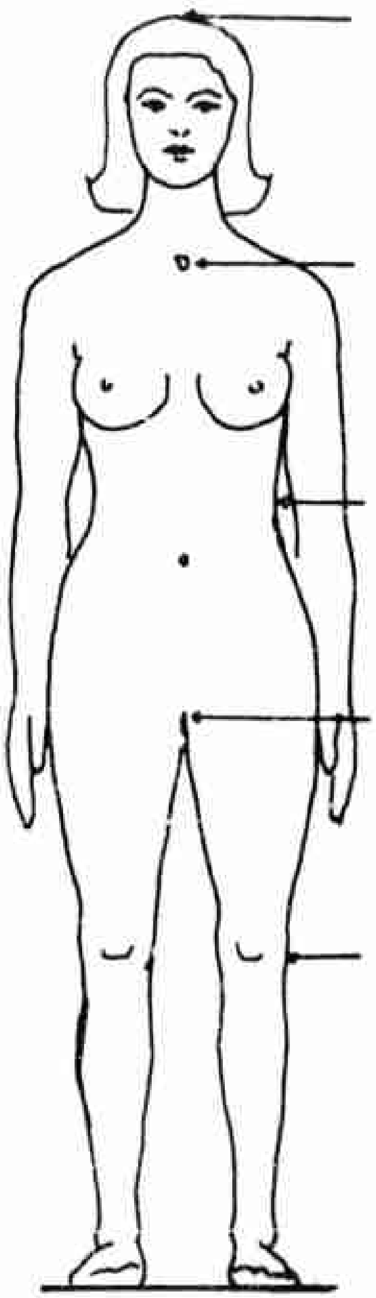
These data were used to determine whether or not our selected subjects as a group were representative of the U.S. population reported in the literature.

The summary of results of anthropometric measurements obtained on this limited sample are compared with results reported by Dreyfuss[12], Roebuck[13], Hertzberg[10], and Daniels[14]. The results reported by Dreyfuss were a general anthropometric compilation of the U.S. adult male and female based on the work of many investigators. Typical of the type of data that is presented in his report are the results shown for the adult U.S. male and female population shown in Tables III and IV. Unfortunately, it is not possible from his work to determine uniquely sample size for each of the characteristics measured since his compilation is derived from many diverse sources.



	2.5%	50%	97.5%	
ADL	156.2	177.0	197.8	Height (cm)
Dreyfuss	162.8	175.8	188.6	
Roebuck	158.0	171.5	187.1	
Hertzberg	162.2	175.5	188.5	
ADL	123.5	141.3	159.1	Height of Suprasternal Notch (cm)
Dreyfuss	132.7	143.8	155.3	
Roebuck	131.3	142.0	156.3	
Hertzberg	128.3	143.2	157.5	
ADL	91.4	103.8	116.2	Height of Iliac Crest (cm)
Hertzberg	95.3	106.1	116.2	
Dreyfuss	90.5	97.2	106.1	Height of Center of Gravity
ADL	70.7	78.9	87.1	Height of Crotch (cm)
Dreyfuss	75.6	83.3	92.2	
Hertzberg	76.3	83.3	92.3	
ADL	40.5	48.1	55.7	Height of top of Fibula
Roebuck	40.2	45.7	50.7	Height of top of Tibia (cm)
Hertzberg	39.2	45.2	48.3	
WEIGHT				
ADL	55.5	77.5	99.5	Total Weight (kg)
Dreyfuss	58.6	73.7	95.0	
Roebuck	56.8	76.0	103.6	
Hertzberg	57.3	73.3	94.5	

TABLE III INTERCOMPARISON OF ANTHROPOMETRIC DATA OBTAINED FROM THE LIMITED ADL ADULT MALE POPULATION SAMPLE AND SIMILAR DATA OBTAINED ON LARGER SAMPLES BY OTHER INVESTIGATORS



	2.5%	50%	97.5%	
ADL	144.7	166.5	188.3	Height (cm)
Dreyfuss	145.7	161.0	173.0	
Daniels	151.0	162.5	173.0	
ADL	122.2	136.0	149.8	Height of Suprasternal Notch (cm)
Dreyfuss	120.0	131.5	141.5	
Daniels	125.6	137.2	153.0	
ADL	91.8	102.4	113.0	Height of Iliac Crest (cm)
Daniels	91.2	100.8	111.8	
ADL	65.7	78.7	91.7	Height of Crotch (cm)
Dreyfuss	65.5	73.3	81.0	
Daniels	70.3	76.7	87.3	
Dreyfuss	41.2	45.3	48.8	Height of Center of Knee Cap (cm)
Daniels	41.5	49.7	57.3	
ADL	39.1	47.7	56.3	Height of top of Fibula (cm)
WEIGHT				
ADL	40.7	61.1	81.5	Total Weight (kg)
Dreyfuss	43.2	61.3	88.6	
Daniels	43.6	56.3	72.0	

TABLE IV INTERCOMPARISON OF ANTHROPOMETRIC DATA OBTAINED FROM THE LIMITED ADL ADULT FEMALE POPULATION SAMPLE AND SIMILAR DATA OBTAINED ON LARGER SAMPLES BY OTHER INVESTIGATORS

The report by Roebuck consists of a compilation of data from a number of different investigators and provides body dimensions of U.S. males as estimated and synthesized for use in commercial aircraft interior design. The data are presented in detail in "The Bioastronautics Data Book."(15) As with Dreyfuss, compilation of the report is a synthesis and it is not possible to determine the sample size for each of the characteristics measured. However, a review of the original sources shows that each of this consists of several thousand subjects.

The Hertzberg report consists of the body dimensions of approximately 4060 flight personnel of the U.S. Air Force while the report by Daniels consists of the body dimensions of 852 women Air Force trainees.

We find that Hertzberg mean values on height and weight are not significantly different statistically from those obtained by Dreyfuss. However, there is a statistically significant difference from the mean height and weights obtained by Roebuck. In addition, in five other tests on the mean values of the height of the suprasternal notch, the height of the crotch and height of the knee, there were statistically significant differences found in the mean value of the military personnel measurements and the general population.

When the mean value data for adult males from the limited ADL sample were compared to the mean values of the three other investigators, no statistically significant differences were found in weight, height, height of suprasternal notch, or iliac crest. There were possible statistically signficant differences in the height of the crotch and knee.

We conclude that the hypothesis that the mean values obtained from the series of ADL measurements could be obtained from any of the three larger distributions appears to be valid.

Adult Female

In the case of the adult female, three distributions were considered. These are the general adult female population described by Dreyfuss, Daniels' data on 852 Women's Air Force trainees and the limited ADL sample.

In testing the variance of these three distributions, we find a significant statistical difference between the variances determined by Daniels and by Dreyfuss for height, weight, height of suprasternal notch, crotch height and knee height. We also find a significant statistical difference between the mean values for height, weight, height of suprasternal notch and crotch height. It was concluded that the 852 Air Force trainees do not represent a good statistical sample of the general adult female population described by Dreyfuss.

In intercomparing the ADL sample with both the Dreyfuss and the Daniels distribution, there were no statistical differences for either the mean values or the variances except that there may possibly be statistically significant differences in height, crotch height and knee height. It was concluded that the limited sample was too small to illustrate adequately the difference between the two possible parent distributions.

RELEVANT BODY CHARACTERISTICS

Although center of mass and center of buoyancy and the distance between them characterizes the net effect of the distribution of mass and buoyancy throughout the length and breadth of the human body, it is apparent that the distribution of either examined segmentally show not only differences between individuals but also marked statistical differences between sexes.

The distribution of mass within the human body cannot be measured in the living subject. Information on cadavers is limited as well as being obtained on smaller individuals than that represented by the limited sample of live subjects.[7,8,9] Attempts to relate masses of individual segments from the cadaver studies to volumes of the segments in our limited sample produced meaningless results. However, segmental volumes and submerged weight were measured for each individual in this study.

VOLUMETRIC RELATIONSHIPS

Buoyancy is a function of volume of water displaced and the density of the water. The results of each segment calculated as percent of total volume are presented in Figures 19 to 27. Analyses showed that there were no statistically significant differences between females and males for head volume, neck volume, head and neck volume combined and volume of lower legs. On the other hand, there were statistically significant differences between chest, upper abdomen, pelvis and thigh volumes. If we accept the data of Dreyfuss which shows that the center

of gravity is slightly below the iliac crest and data from this study which shows that the center of buoyancy is within 1 to 3 cm of the center of gravity (see Figure 31), we find that the differences between the chest plus upper abdomen volumes above the iliac crest and the pelvis plus thigh volumes below the iliac crest are working in opposite directions in the two sexes. This is further illustrated in Figure 27 which shows the differences between males and females in volumes below the iliac crest. This results in males having a greater submerged stability than females and partially explains the results of the stability measurements which showed that in addition to volumetric effects, males have a higher degree of stability than females.

STABILITY RELATIONSHIPS

Figure 28 illustrates typical results of the stability experiments on male and female subjects in the "relaxed state." In the prone angles of rotation the head was in flexion while in the supine angles the head was held in extension. The arms and legs were allowed to attain positions according to each subject's idea of the "relaxed state." Mean equilibrium angles for adult males were -6° supine and $+16^{\circ}$ prone. Mean equilibrium angles for adult females was -3° supine and $+22^{\circ}$ prone.

Figure 29 illustrates the percentage distribution of the male and female adult population (based on the limited sample) for submerged forward equilibrium angles (head flexed) and shows that females float at a significantly greater forward angle than males ($p < 0.01$). These data indicate that the center of buoyancy for both males and females in forward equilibrium angles are above the center of gravity and dorsal to

to the center line of the long axis of the trunk. In females the center of buoyancy is therefore relatively more dorsal than in the males.

Figure 30 illustrates the percentage distribution of the male and female adult population (based on the limited sample) for the torque required to rotate fully submerged subjects with lungs at residual volume to a prone and supine angle of 30° and shows that females require a significantly smaller couple than males to achieve rotation ($p < 0.01$). This is in consonance with the fact that their volume is less and their center of buoyancy is closer to the center of gravity. Figure 31 is a plot of the probability distribution for the calculated values of the distance from the center of buoyancy to the center of gravity for the limited sample.

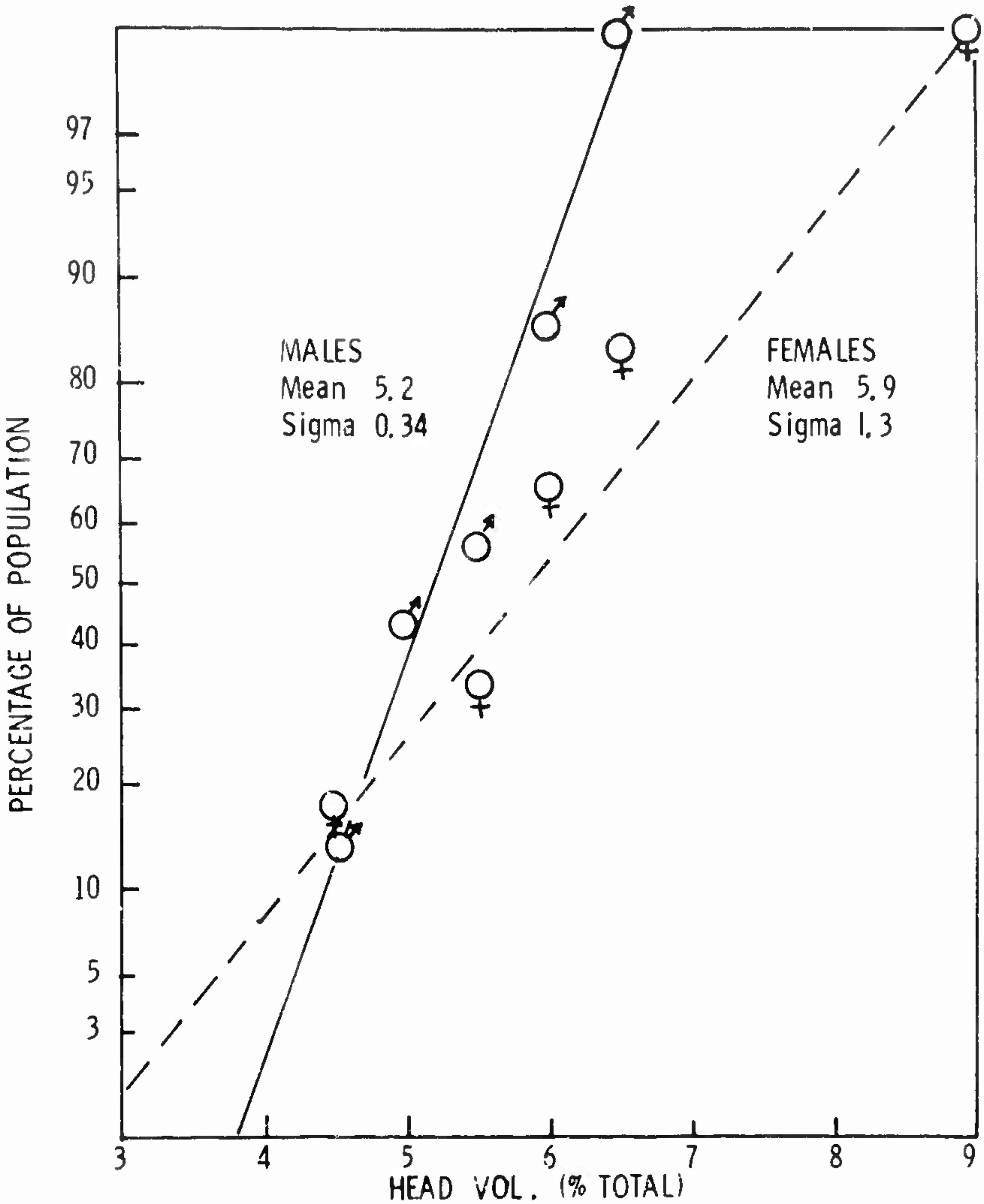


FIGURE 19 PERCENT OF POPULATION WITH HEAD VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED

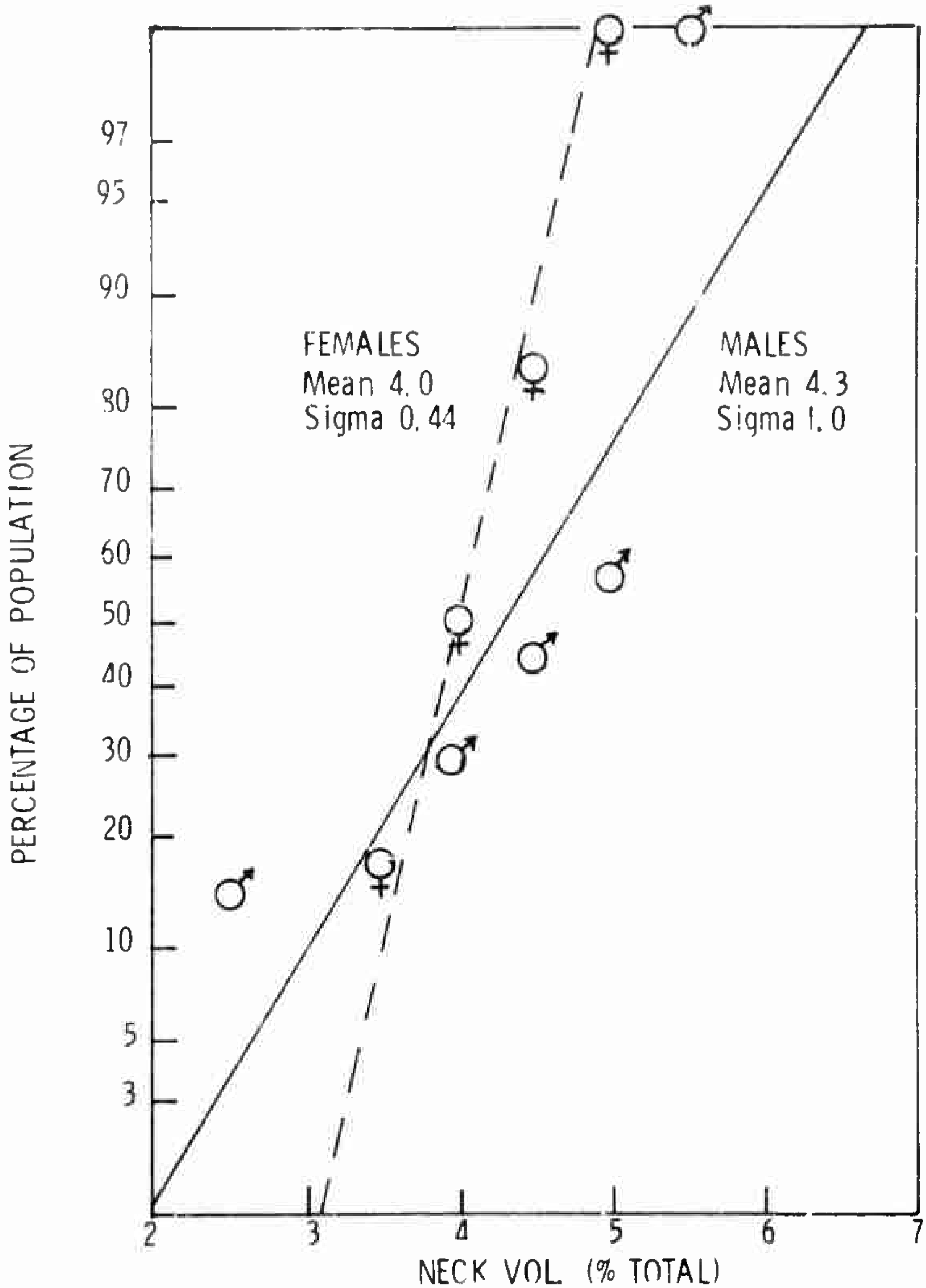


FIGURE 20 PERCENT OF POPULATION HAVING NECK VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

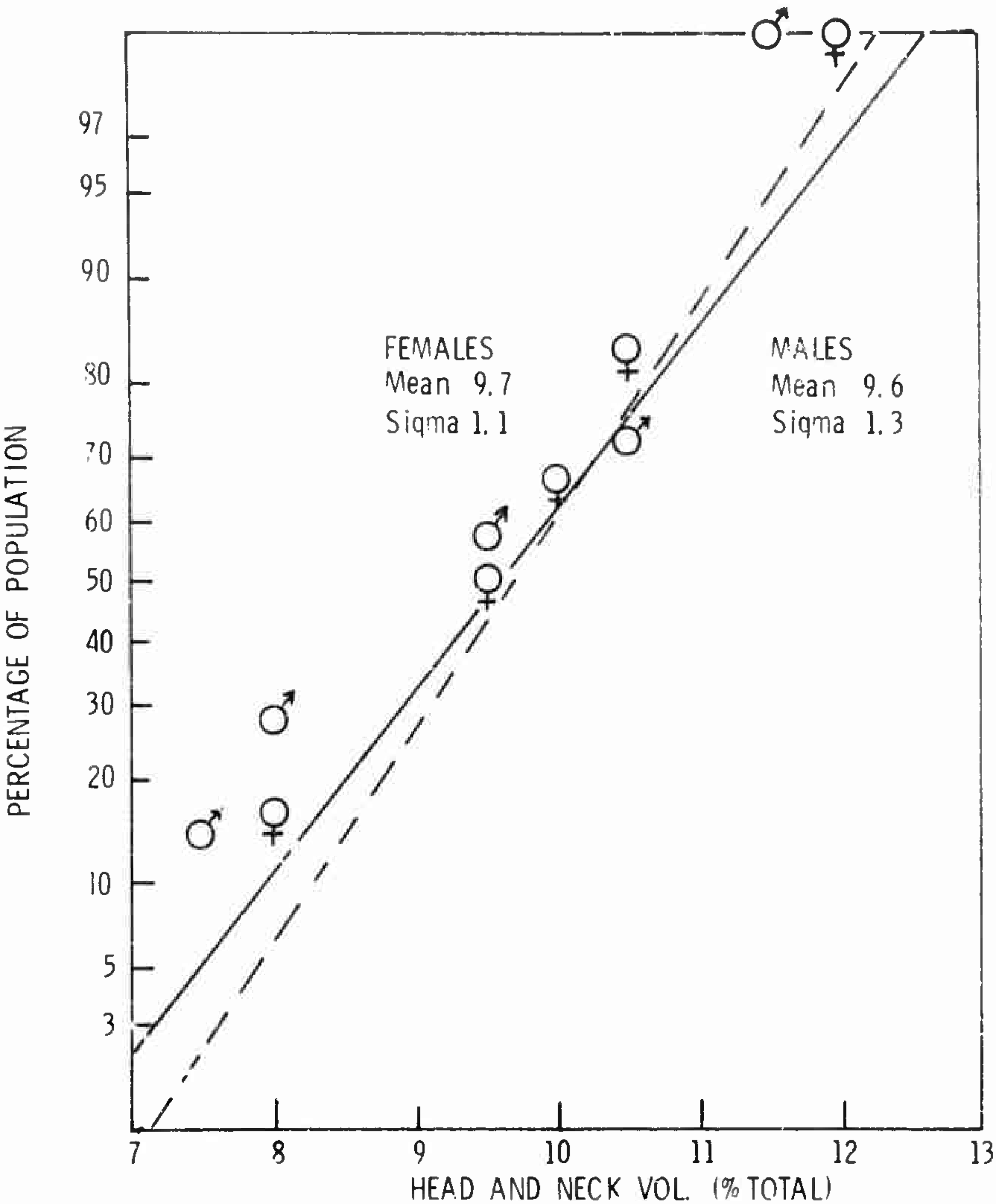


FIGURE 21 PERCENT OF POPULATION HAVING HEAD PLUS NECK VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

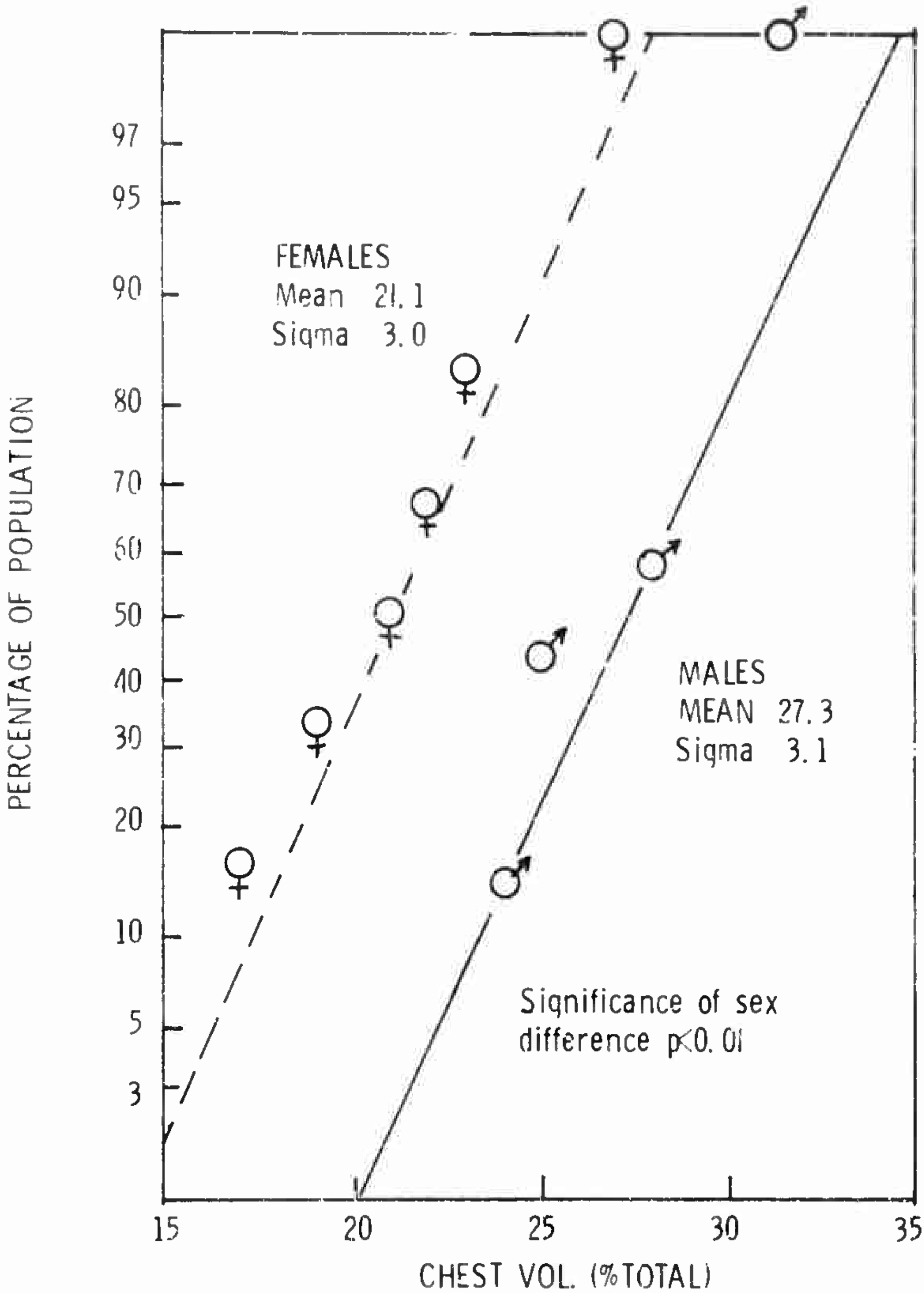


FIGURE 22 PERCENTAGE OF POPULATION HAVING CHEST PLUS ARMS VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

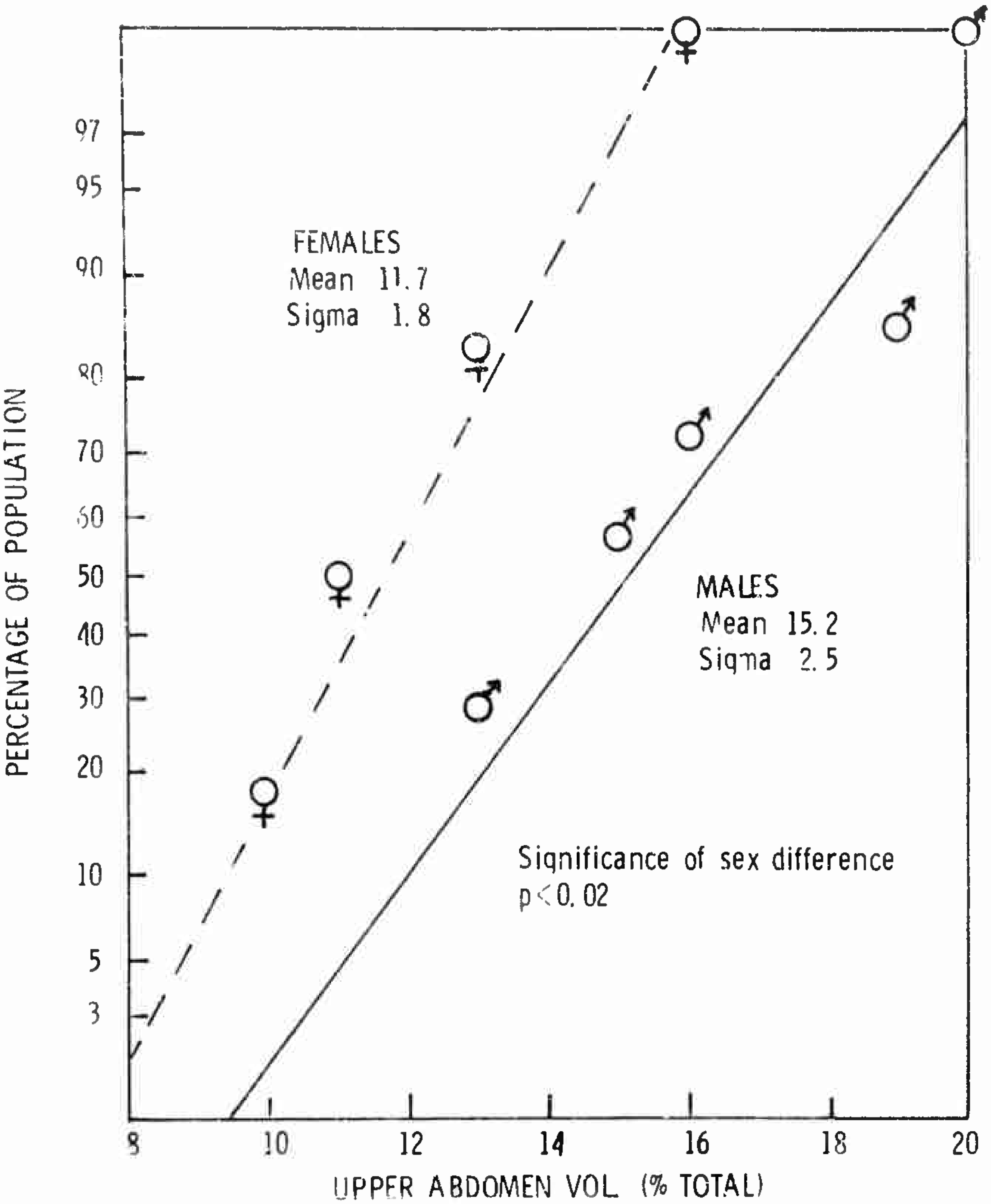


FIGURE 23 PERCENTAGE OF POPULATION WITH UPPER ABDOMEN VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED ABOVE

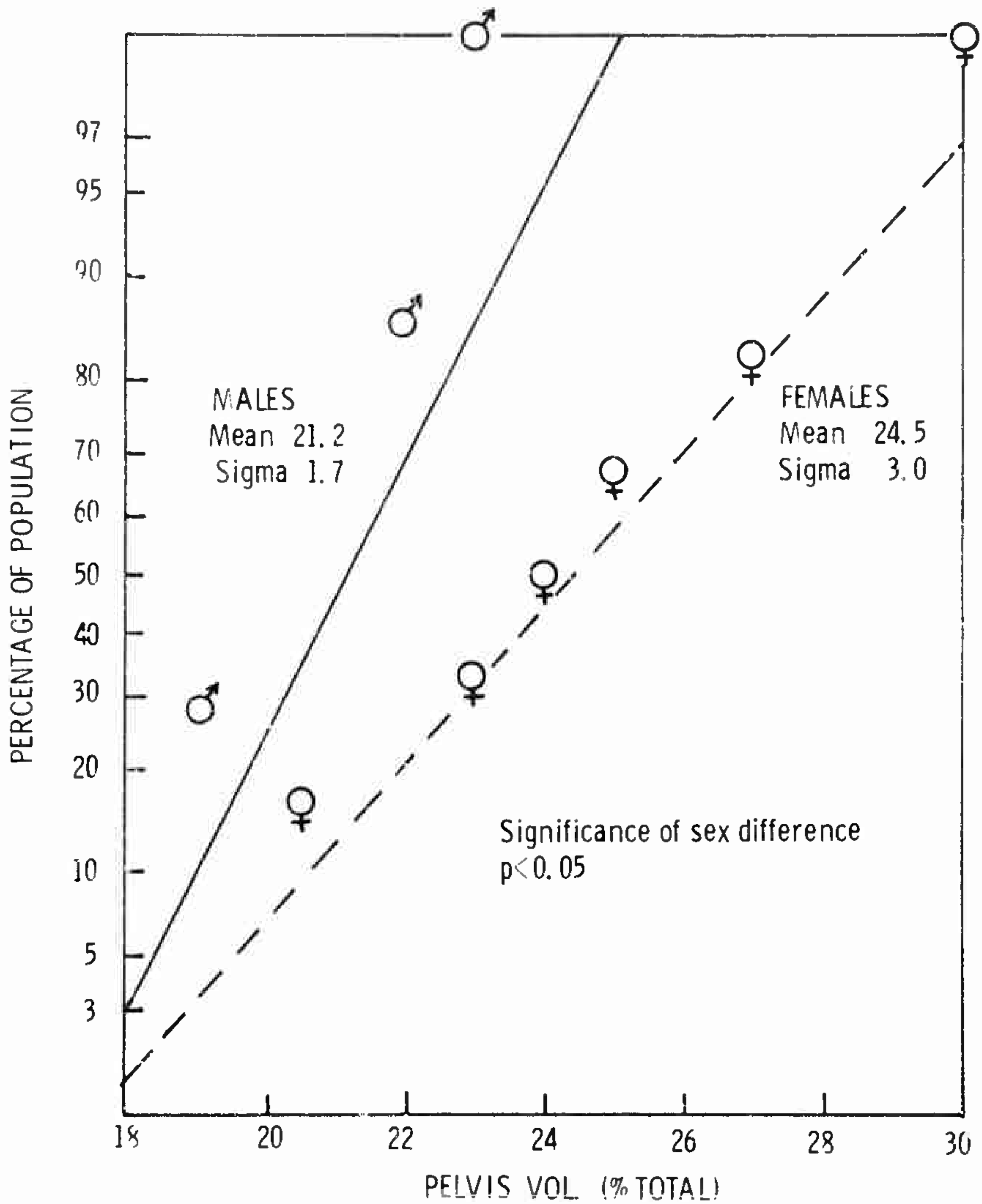


FIGURE 24 PERCENTAGE OF POPULATION WITH PELVIC VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

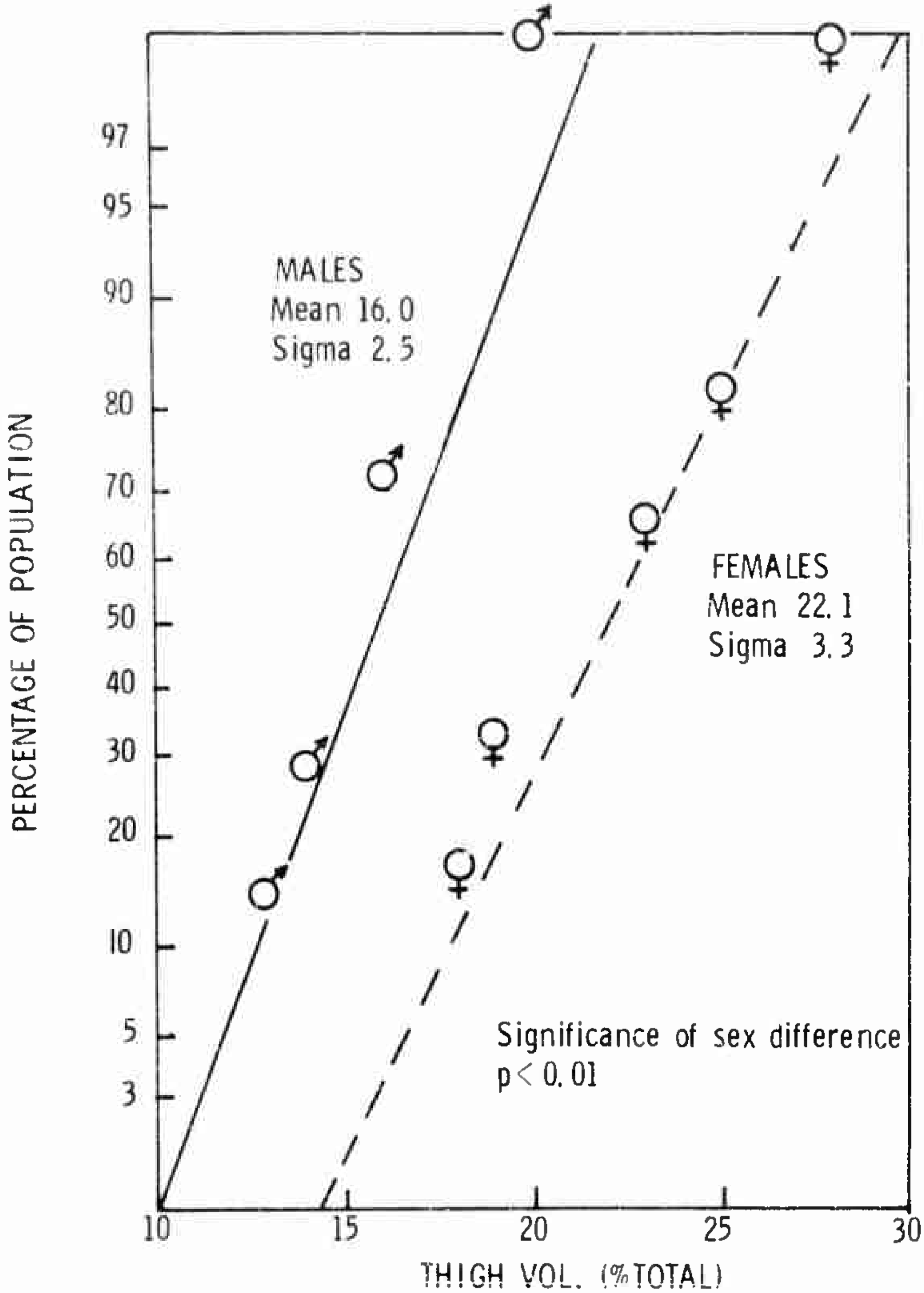


FIGURE 23 PERCENTAGE OF POPULATION WITH THIGH VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

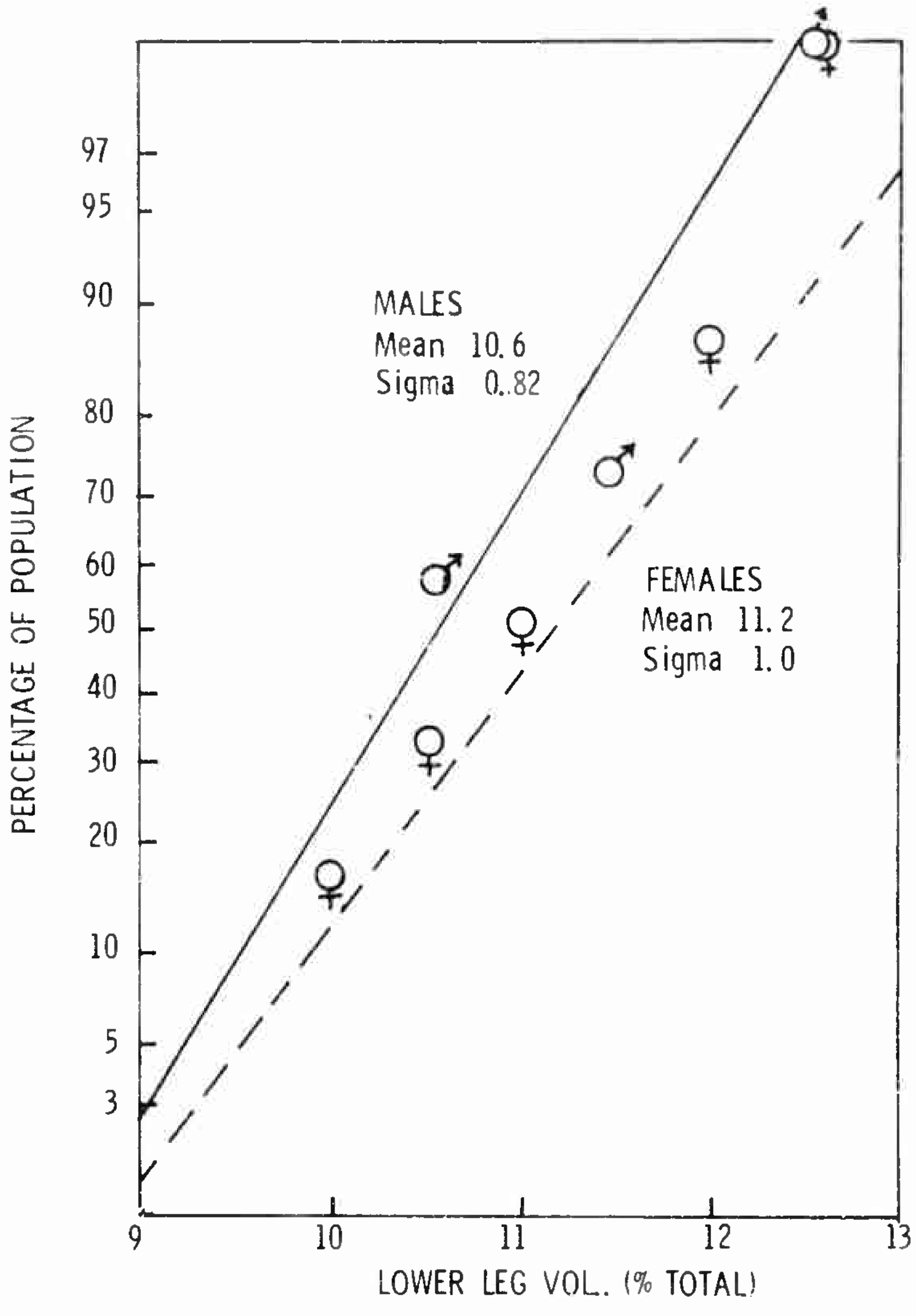


FIGURE 26 PERCENTAGE OF POPULATION WITH LOWER LEG VOLUME (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE

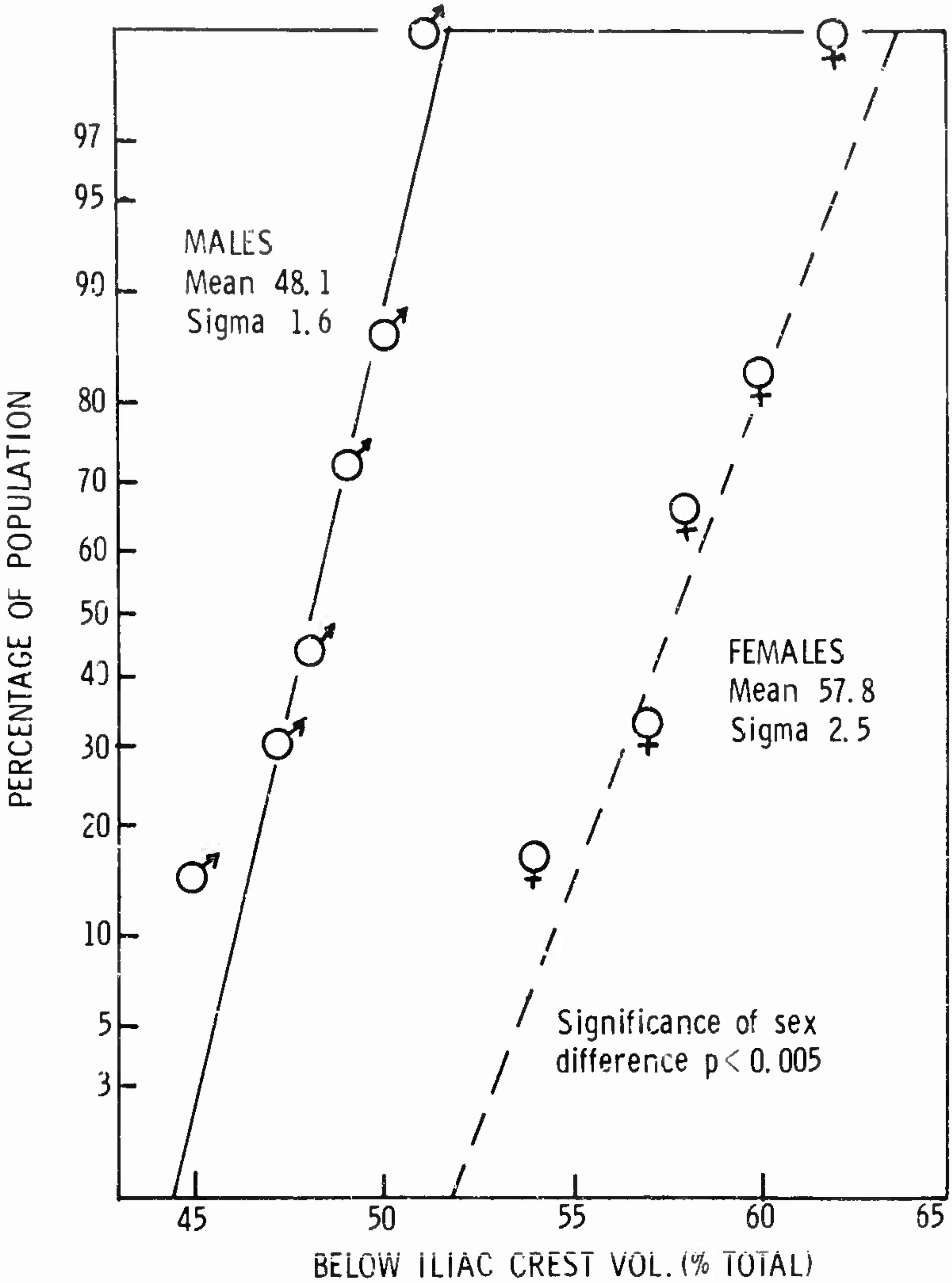
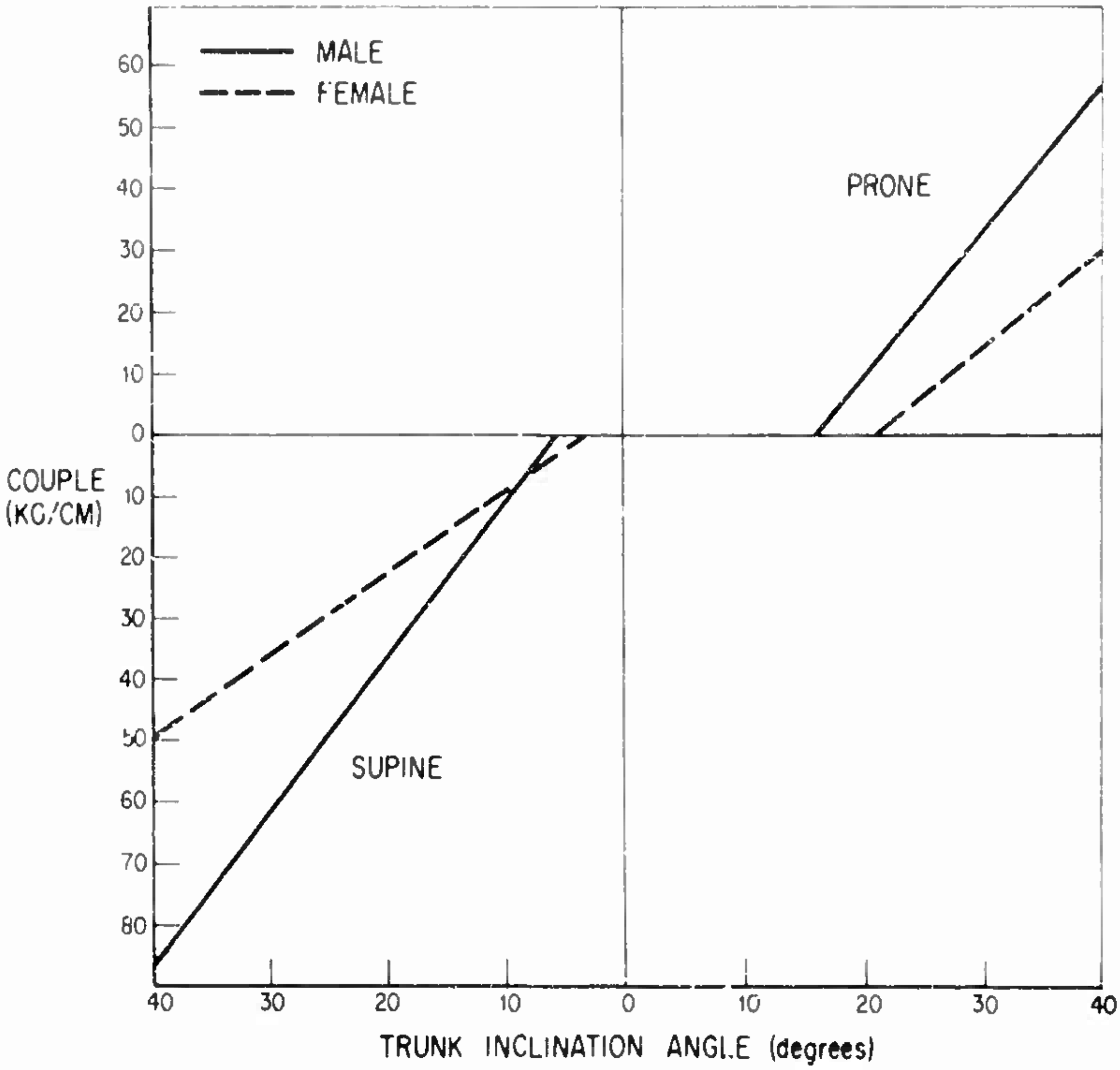


FIGURE 27 PERCENTAGE OF POPULATION WITH VOLUME BELOW THE ILIAC CREST (EXPRESSED AS PERCENT OF TOTAL BODY VOLUME) EQUAL TO OR LESS THAN INDICATED VALUE



TYPICAL COUPLE (KG/CM) REQUIRED TO ROTATE MALE AND FEMALE SUBJECTS TO VARIOUS PRONE AND SUPINE ANGLES

Figure 27

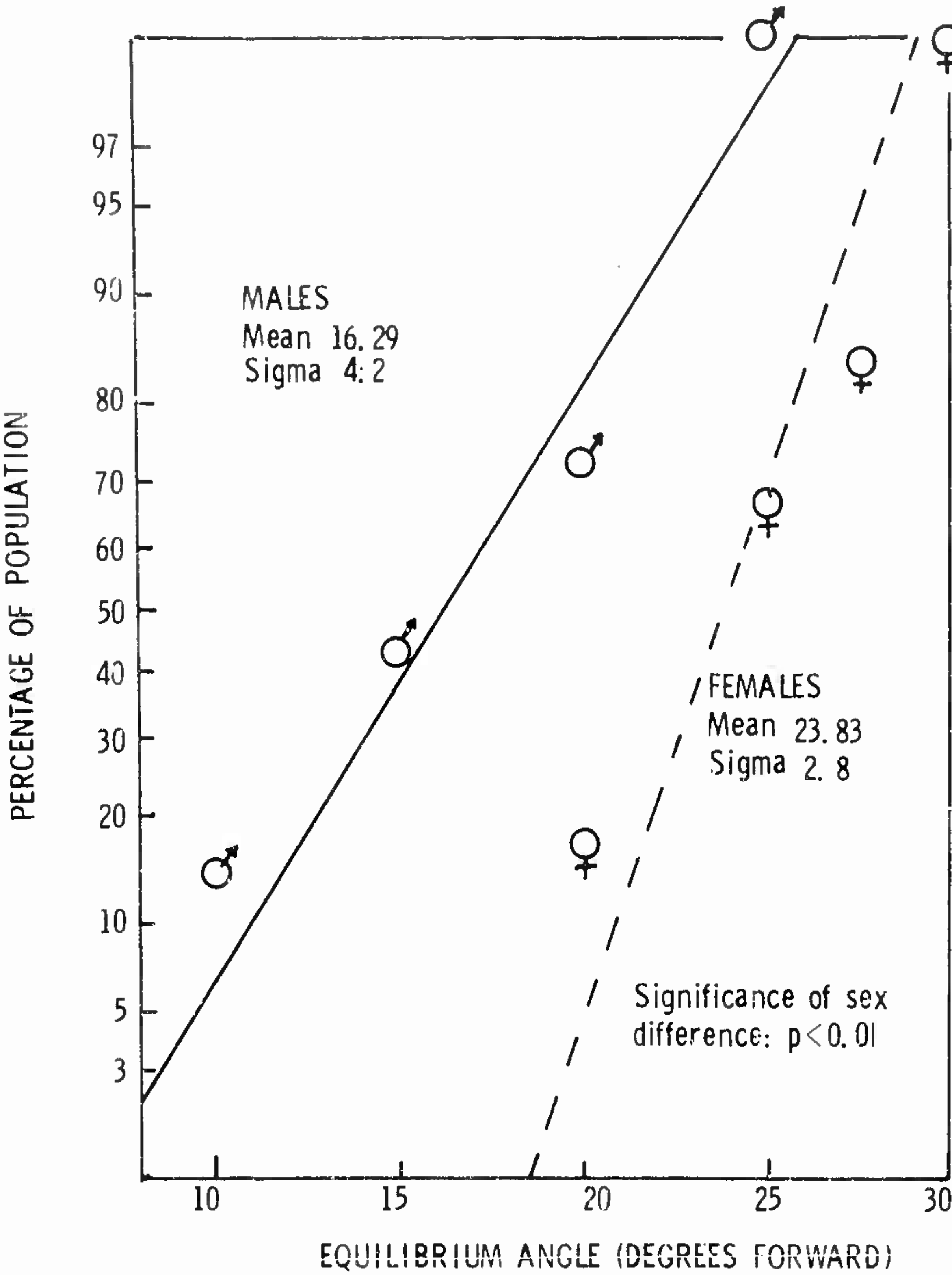


FIGURE 29

PERCENTAGE OF POPULATION WITH A SUBMERGED EQUILIBRIUM ANGLE EQUAL TO OR LESS THAN INDICATED VALUE

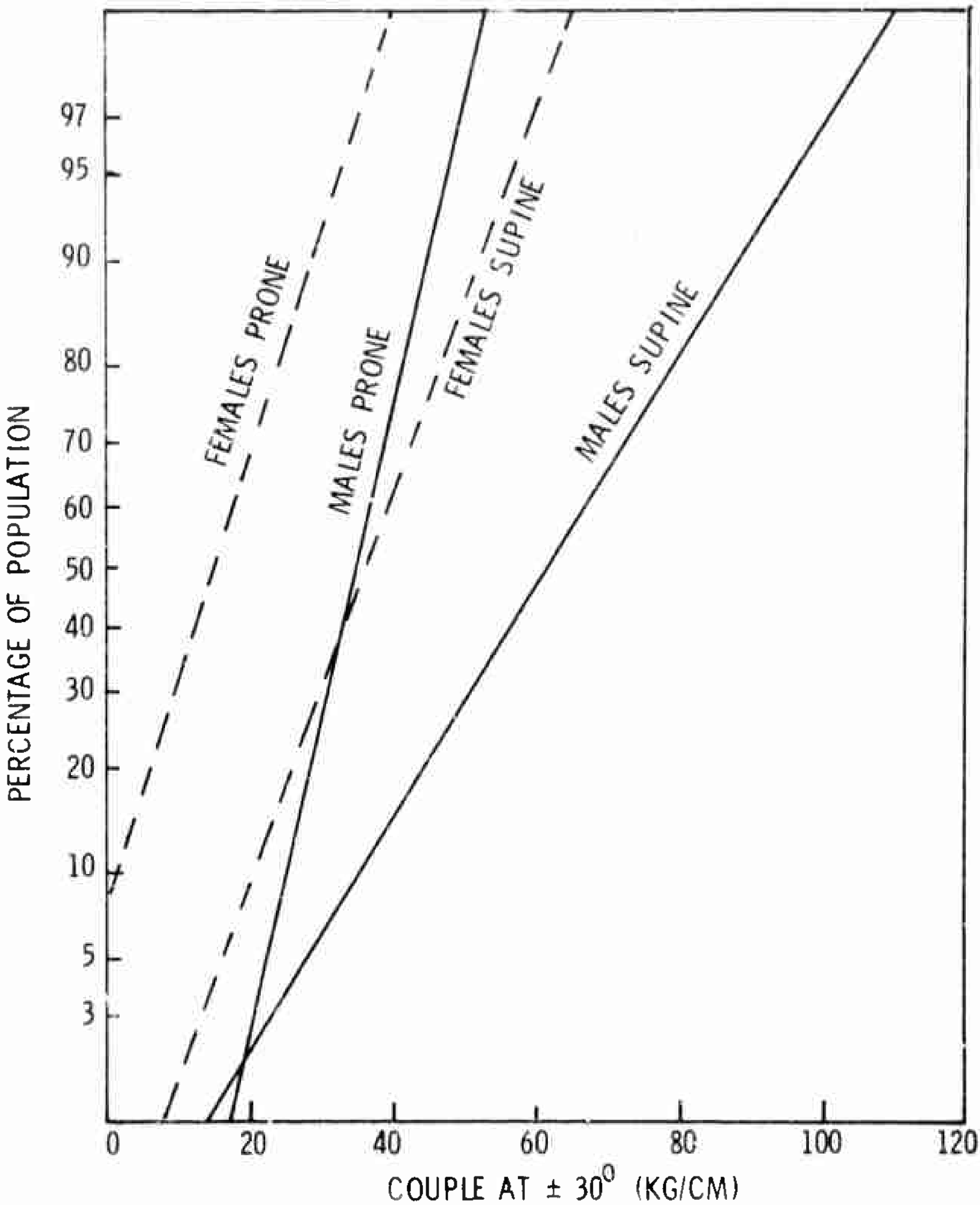


FIGURE 30 PERCENTAGE OF POPULATION WITH A SUBMERGED BODY COUPLE AT ± 30° EQUAL TO OR LESS THAN INDICATED VALUE

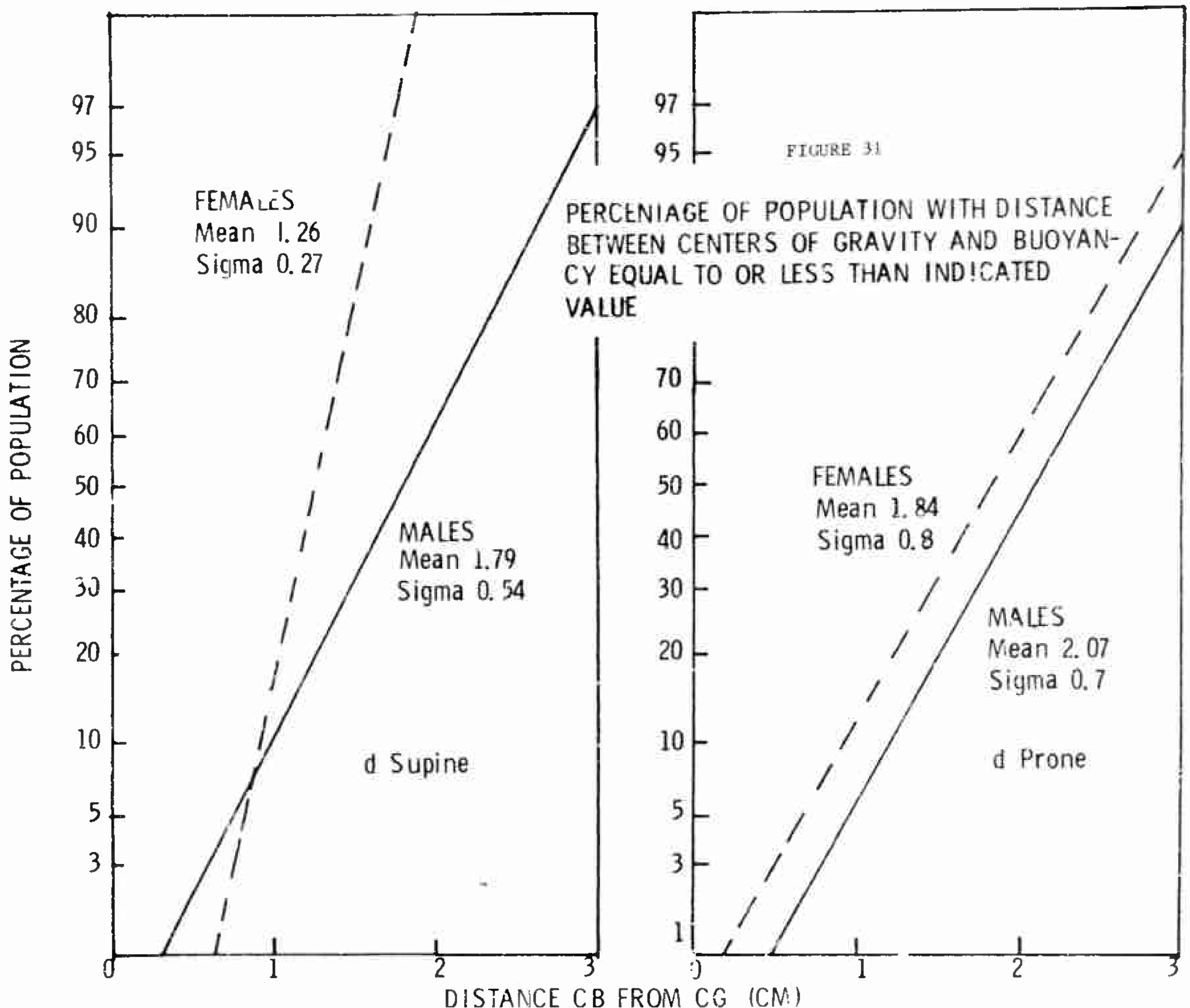


FIGURE 31

PERCENIAGE OF POPULATION WITH DISTANCE BETWEEN CENTERS OF GRAVITY AND BUOYANCY EQUAL TO OR LESS THAN INDICATED VALUE

DISCUSSION

The method of selection of a limited adult male and female population to span the human body characteristics of the general population proved to be effective, at least in terms of anthropometric measures and, therefore, presumably of these measures (not available in the literature) required for analyzing the buoyancy and stability problem.

The buoyancy problem resolved itself to two physically measurable quantities, namely, submerged weight and volumes of head and neck, i.e., that part of the body required to be out of the water for survival purposes. Although measurements required to resolve the buoyancy problem were performed in fresh water at residual lung volume, separate respiratory and volume measurements allow calculation of buoyancy requirements for functional residual volume, total lung volume and for salt water.

The stability problem resolved itself into one concerned with rotating an individual from a prone position, with head fully flexed, into a range of orientations conducive to his survival and maintaining him in this orientation. It was found that stability requirements were a function of the amount of added buoyancy and the position of its center of buoyancy in relation to the front of the trunk. Solution of the stability problem depends on measurable quantities of the human body and measurable quantities of a PFD. A PFD can, therefore, be characterized as to the percentage of the population which it can serve as a family of curves

Although the selection of subjects appeared to be effective in spanning the variabilities of characteristics of the general population, it must again be emphasized that the results presented in this report based on a limited sample cannot be extrapolated to the general boating population and used as criteria for the design of personnel flotation devices without verification based on a statistical sample of the boating population.

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APPENDIX A

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APPENDIX B

COMPUTER PROGRAM

Table B-1 is a listing of the computer program that has been written to solve inequalities (10), (12) and (16) on pages 42 and 43 for each subject. Satisfying these three inequalities by a PFD supplying a fixed amount of buoyancy and a fixed center of buoyancy assumes

- The subject is rotated toward vertical from the prone equilibrium that would prevail without a PFD.
- The subject is rotated through vertical from the prone to the supine position.
- The subject attains a supine equilibrium at less than -90°.

It should be noted that the present theoretical development and experimental data have been based on lung volume corresponding to residual volume (i.e., fully deflated). The effects of changing lung volume on stability have not been investigated as yet.

Table B-2 is an example of the series of calculations done for one particular buoyancy for the 1969 ADL limited population. In this case this added PFD buoyancy was defined as Bf = 12.00 kilograms (~ 26 pounds). The computer then takes the following data for each subject.

Figure 1 in text (pg 19)	Definition	
	A	Height of suprasternal notch - subject vertical (cm)
	B	Height of CG - subject vertical (cm)
h	H	Subject height (cm)
p	P	Distance from external meatus to suprasternal notch - head flexed (cm)
S	S	Submerged weight (kg)
θ_f	THF	Forward equilibrium angle (degrees)
$\rho_w V_T d_f(\theta_f) \cdot \theta_f$	STF	Prone stiffness (kg cm)
$\rho_w V_T d_b(\theta_b)$	STB	Supine stiffness $\left(\frac{\text{kg cm}}{\text{radian}}\right)$

Using these data, for each subject, the computer then procceds to calculate the required values of the coordinates X and Y for the location of the PFD center of buoyancy that satisfy the three inequalities.

```
    3 READ(9,2) BF
      IF(BF) 100,100,10
   10 WRITE(9,40) BF
    9 READ(1,1) NS
      IF(NS) 3,11,11
   11 READ(1,2) A,B,H,P
      READ(1,2) S,THF,STF,STB
      WRITE(9,20) NS,A,B,H,P
      WRITE(9,30) S,THF,STF,STB
      SBF = S/BF
      YP2 = -STB/BF - SBF - (1.0-SBF)*P
      THR = THF/57.3
      X0 = 0.7*P*(1.0-SBF) + STF/BF
      TAN = SIN(THR)/COS(THR)
      GAM = 1.0/TAN
      ALPHA = 0.7*P*((1.0-SBF)*(1.0+TAN))
     +  - (A-B-H/8.0)*SBF*TAN
      DEL =ALPHA/TAN
      WRITE(9,50) X0
      WRITE(9,60) DEL,GAM
      WRITE(9,70) YP2
      GO TO 9
    1 FORMAT(I5)
    2 FORMAT(4F10.2)
   20 FORMAT('SUBJECT NO.',I5,/,'A= ',F7.2,
     + ', B= ',F7.2,', H= ',F7.2,', P= ',F7.2)
   30 FORMAT('S= ',F7.2,' THF= ',F5.1,
     + ' DEG.,  STF= ',F7.2,' STB= 'F7.2,/)
   40 FORMAT('BF= ',F7.2,' KILOGRAMS',//)
   50 FORMAT('X MUST BE GREATER THAN',F7.2)
   60 FORMAT('Y MUST BE GREATER THAN',F7.2,' -',F7.2,' X')
   70 FORMAT('Y(-PI/2) MUST BE GREATER THAN',F7.2,///)
  100 STOP
      END
```

TABLE B-1 LISTING OF COMPUTER PROGRAM FOR LOCATING PFD CENTER OF BUOYANCY

```
1 12.

BF=     12.00 KILOGRAMS

DEFINE FILE( S)
1=BODS

SUBJECT NO.      1
A=  158.70,  B=   111.40,  H=   187.60,  P=    20.30
S=     2.24  THF=    9.0 DEG.,   STF=    24.00  STB=   112.00

X MUST BE GREATER THAN   13.56
Y MUST BE GREATER THAN   81.20 -    6.31 X
Y(-PI/2) MUST BE GREATER THAN  -26.03


SUBJECT NO.      2
A=  136.50,  B=   161.90,  H=   168.00,  P=    17.80
S=     3.72  THF=   15.0 DEG.,   STF=    59.00  STB=   121.00

X MUST BE GREATER THAN   13.51
Y MUST BE GREATER THAN   36.47 -    3.73 X
Y(-PI/2) MUST BE GREATER THAN  -22.68


SUBJECT NO.      3
A=  133.00,  B=    99.40,  H=   161.00,  P=    17.20
S=     2.61  THF=   22.0 DEG.,   STF=    89.00  STB=    85.50

X MUST BE GREATER THAN   16.84
Y MUST BE GREATER THAN   29.81 -    2.48 X
Y(-PI/2) MUST BE GREATER THAN  -20.80


SUBJECT NO.      4
A=  135.90,  B=    95.90,  H=   165.40,  P=    17.80
S=     3.03  THF=   12.0 DEG.,   STF=    32.00  STB=   117.00

X MUST BE GREATER THAN   11.98
Y MUST BE GREATER THAN   48.26 -    4.70 X
Y(-PI/2) MUST BE GREATER THAN  -23.31
```

TABLE B-2 CALCULATION OF ADMISSIBLE LOCATIONS FOR PFD CENTER OF BUOYANCY FOR EACH SUBJECT WITH LUNGS AT RESIDUAL CAPACITY AND IN FRESH WATER - ADDITIONAL BUOYANCY 26 POUNDS

```
SUBJECT NO.      5
A=  145.40,  B=   108.00,  H=   178.10,  P=    18.40
S=     2.02  THF=  20.0 DEG.,   STF=   40.00  STB=   106.50

X MUST BE GREATER THAN   14.05
Y MUST BE GREATER THAN   37.60 -    2.75 X
Y(-PI/2) MUST BE GREATER THAN -24.35


SUBJECT NO.      6
A=  141.20,  B=   106.70,  H=   176.00,  P=    21.00
S=     3.74  THF=  19.0 DEG.,   STF=   40.00  STB=   212.00

X MUST BE GREATER THAN   13.45
Y MUST BE GREATER THAN   35.61 -    2.90 X
Y(-PI/2) MUST BE GREATER THAN -32.43


SUBJECT NO.      7
A=  158.80,  B=   120.80,  H=   193.00,  P=    19.70
S=     0.77  THF=  17.0 DEG.,   STF=   33.00  STB=   143.00

X MUST BE GREATER THAN   16.07
Y MUST BE GREATER THAN   54.23 -    3.27 X
Y(-PI/2) MUST BE GREATER THAN -30.42


SUBJECT NO.      8
A=  152.70,  B=   111.50,  H=   187.30,  P=    20.00
S=     3.33  THF=  17.0 DEG.,   STF=   57.00  STB=   177.00

X MUST BE GREATER THAN   14.86
Y MUST BE GREATER THAN   38.27 -    3.27 X
Y(-PI/2) MUST BE GREATER THAN -29.48
```

TABLE B-2 (Cont.)

```
SUBJECT NO.    10
A=   144.20,  B=   110.50,  H=   177.20,  P=    17.50
S=      1.62  THF=   23.0  DEG.,   STF=    47.00  STB=    62.50

X MUST BE GREATER THAN   14.51
Y MUST BE GREATER THAN   34.00 -    2.36 X
Y(-PI/2) MUST BE GREATER THAN -20.48


SUBJECT NO.    11
A=   143.70,  B=   106.40,  H=   176.80,  P=    19.40
S=      2.10  THF=   19.0  DEG.,   STF=   130.00  STB=   102.00

X MUST BE GREATER THAN   22.04
Y MUST BE GREATER THAN   41.08 -    2.90 X
Y(-PI/2) MUST BE GREATER THAN -24.68


SUBJECT NO.    12
A=   136.20,  B=   103.50,  H=   167.60,  P=    18.10
S=      1.64  THF=   26.0  DEG.,   STF=    42.00  STB=    72.00

X MUST BE GREATER THAN   14.44
Y MUST BE GREATER THAN   31.76 -    2.05 X
Y(-PI/2) MUST BE GREATER THAN -21.76


SUBJECT NO.    13
A=   132.80,  B=   100.00,  H=   162.00,  P=    17.10
S=      2.01  THF=   24.0  DEG.,   STF=    33.00  STB=    85.00

X MUST BE GREATER THAN   12.72
Y MUST BE GREATER THAN   30.25 -    2.25 X
Y(-PI/2) MUST BE GREATER THAN -21.49
```

TABLE B-2 (Cont.)

```
SUBJECT NO.    14
A=   131.80,  B=    98.30,  H=   161.80,  P=    17.80
S=      1.42  THF=   28.0  DEG.,   STF=    72.00  STB=    59.00

X MUST BE GREATER THAN   16.99
Y MUST BE GREATER THAN   30.08  -    1.88 X
Y(-PI/2) MUST BE GREATER THAN -20.73


SUBJECT NO.    15
A=   123.80,  B=    90.20,  H=   155.20,  P=    18.70
S=      1.79  THF=   23.0  DEG.,   STF=    97.00  STB=    62.50

X MUST BE GREATER THAN   19.22
Y MUST BE GREATER THAN   35.26  -    2.36 X
Y(-PI/2) MUST BE GREATER THAN -21.27


SUBJECT NO.    16
A=   127.60,  B=    96.50,  H=   157.50,  P=    21.50
S=     -1.67  THF=    3.0  DEG.,   STF=    55.00  STB=    69.00

X MUST BE GREATER THAN   17.54
Y MUST BE GREATER THAN  258.59  -   19.08 X
Y(-PI/2) MUST BE GREATER THAN -24.40


! 0

STOP,
?
```

TABLE B-2 (Cont.)

APPENDIX C

DATA SUMMARY

During the course of the experimental program, large amounts of data were accumulated on each of the individuals in the 1969 ADL limited population. Since the population was of limited size, it is not reasonable to attempt to generalize on the results. The data were accumulated and used to illustrate a method of approach to a statistical problem. They do not provide a definitive data set upon which to base criteria for judgment of adequacy of PFD buoyancy and stability. The data are therefore not fully reported in this report; however, the types of data collected and their treatment, is illustrated in Table C-1.

Subject Number	EQUILIBRIUM FLOTATION ANGLES SUPINE θ_b (degrees)	EQUILIBRIUM FLOTATION ANGLES PRONE θ_f (Degrees)	COUPLE SLOPE SUPINE $\rho_w V_T d(\theta_b)$ $\frac{\text{kg-cm}}{\text{Radian}}$	COUPLE SLOPE PRONE $\rho_w V_T d(\theta_f)$ $\frac{\text{kg-cm}}{\text{Radian}}$	TOTAL BUOYANCY $\rho_w V_T$* kg	DISTANCE CB-CG SUPINE $d(\theta_b)$ cm	DISTANCE CB-CG PRONE $d(\theta_f)$ cm
Male Subject Number							
1	+3	9	112.0	105.2	101.7	1.10	1.04
2	0	15	121.0	166.7	59.3	2.04	2.82
3	-5	22	86.4	207.8	72.3	1.20	2.90
4	-10	12	117.0	146.7	70.7	1.70	2.10
5	-4	20	94.2	119.2	73.1	1.30	1.60
6	-7	19	157.2	104.9	82.7	1.90	1.30
7	+2	17	142.8	126.0	115.3	1.2	1.1
MEAN	-3.3	+16.3				1.68	2.04
SIGMA	4.6	4.5				.53	.74
Female Subject Number							
10	+6	23	63	107.0	75.7	0.84	1.42
11	0	19	103.8	202.0	70.6	1.47	2.86
12	0	26	71.8	64.3	52.3	1.37	1.23
13	0	24	86.5	140.0	50.9	1.70	2.75
14	-8	29	59.0	101.9	52.6	1.12	2.11
15	-12	23	62.6	174.2	38.2	1.64	4.56
16	-15	3	69.3	55.5	61.8	1.12	0.90
MEAN	-2.9	20.7 (24.2)				1.27	1.88
SIGMA	7.5	8.9 (3.7)				.33	.87

* ρ_w assumed as 1.0 kg/liter.

TABLE C-1 ILLUSTRATIVE DATA ON ADL SAMPLE POPULATION

APPENDIX D

SUBMERGED WEIGHT MOMENTS

In the text equation (7) on page 33 gives the submerged weight moment as $S\left(m - \frac{h}{8}\right) \sin\theta$ for the head flexed body configuration. The submerged weight moment for the head extended configuration is given as $S\left(m - \frac{\beta W_a + \alpha W_\ell}{W}\right)$ in equation (8). It is seen directly from Figures 7 and 8 that these moments taken about A are simply the submerged weight acting at CG(θ) at a horizontal distance from A given by $m\sin\theta$ less the horizontal displacement of the CG in going from the erect position (e.g., $\theta = 0$) to an inclination angle θ. It therefore remains to show that the horizontal displacement of the CG is $\frac{h}{8} \sin\theta$ in the head flexed configuration, and $\frac{\rho W_a + \alpha W_\ell}{W} \sin\theta$ in the head extended configuration.

HEAD FLEXED

It is observed that if a subject balances on a horizontal bar with arms horizontal and with head flexed that the body configuration is identical to that shown in Figure 7 in the text. Balance occurs when the subject's CG is directly below the bar and occurs at a height corresponding closely to that of the iliac crest. It is further observed that when balance occurs, that the angle between the legs and the horizontal and the trunk and the horizontal are approximately equal. If it is assumed that the center of gravity of the upper and lower halves of the body occur at $\frac{h}{4}$ above and below the iliac crest, then the balance situation is as shown in Figure D-1.

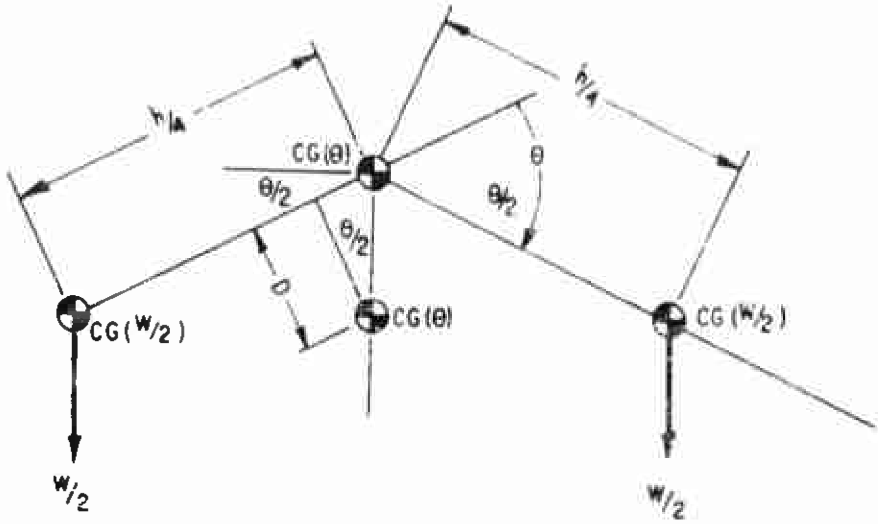

FIGURE D-1 DIAGRAM OF BALANCE CONDITION FOR TRUNK INCLINATION ANGLE θ

In this figure CG(O) is the location of the CG of the subject when he is erect. When he balances with his trunk inclined at an angle θ to his legs, his CG drops down to a position CG(θ). Therefore, his CG has moved forward with respect to his legs a distance D. This distance D corresponds to the horizontal displacement of his CG when the subject floats in the prone position with head flexed. From the geometry of Figure D-1 it is seen that

$$D = \frac{h}{4} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \qquad \text{(D-1)}$$

However,

$$\sin \frac{\theta}{2} \cos \frac{\theta}{2} = \frac{1}{2} \sin \theta \qquad \text{(D-2)}$$

Therefore

$$D = \frac{h}{8} \sin \theta \qquad \text{(D-3)}$$

This last result is the approximation used in equation (7) to represent the horizontal displacement of the subject's center of gravity with inclination θ in the head flexed configuration.

HEAD EXTENDED

In equation (8) the quantity $\frac{\beta W_a + \alpha W_\ell}{W_T}$ sin θ represents the horizontal distance between CG(0) and CG(θ) when an erect subject with head extended is rotated from the erect position to a supine position with a trunk inclination angle θ. In the erect position, the GG of the body less arms and legs, the arms and the lower leg are all on the body centerline. In the supine position, the location of the CG of the body less arms and legs is unchanged. The CG of both the arms and the legs are moved back and upward from their original location. In Figure 8, it is seen that the arms and legs are rotated backward through and angle θ. It is assumed that the CG of the lower leg is a distance α from the knee and the CG of the arms is a distance β from the shoulder. It is further assumed that the distance γ is the distance from the body centerline to GG(θ) and δ is the distance along the body centerline from CG(0) to CG(θ).

One can now calculate the change in moments in going from CG(0) to CG(θ) as the arms and legs are rotated through an angle θ. The calculation is done about axes parallel and perpendicular to the axis of the trunk passing through CG(θ). It follows that:

$$W_a(\beta \sin\theta - \gamma) + W_\ell(\alpha \sin\theta - \gamma) = (W_T - W_a - W_\ell)\gamma \tag{D-4}$$

therefore,

$$\gamma = \frac{(W_a\beta + W_\ell\alpha)\sin\theta}{W_T} \tag{D-5}$$

$$W_a(\beta - \beta\cos\theta - \delta) + W_\ell(\alpha - \alpha\cos\theta - \delta) = (W_T - W_a - W_\ell)\,\delta \tag{D-6}$$

rearranging terms

$$(W_a\beta + W_\ell\alpha)\,(1 - \cos\theta) = W_T\,\delta \tag{D-7}$$

and solving for δ, one obtains:

$$\delta = \left(\frac{W_a\beta + W_\ell\alpha}{W_T}\right)(1 - \cos\theta) \tag{D-8}$$

Referring again to Figure 8, it is observed that the horizontal displacement of the center of gravity when the body is inclined in the supine direction is given by

$$\epsilon = \gamma\cos\theta + \delta\sin\theta \tag{D-9}$$

or

$$\epsilon = \left(\frac{W_a\beta + W_\ell\alpha}{W_T}\right)\left\{\sin\theta\cos\theta + \sin\theta - \sin\theta\cos\theta\right\} \tag{D-10}$$

and finally

$$\epsilon = \left(\frac{W_a\beta + W_\ell\alpha}{W_T}\right) \tag{D-11}$$

which is the desired result.

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